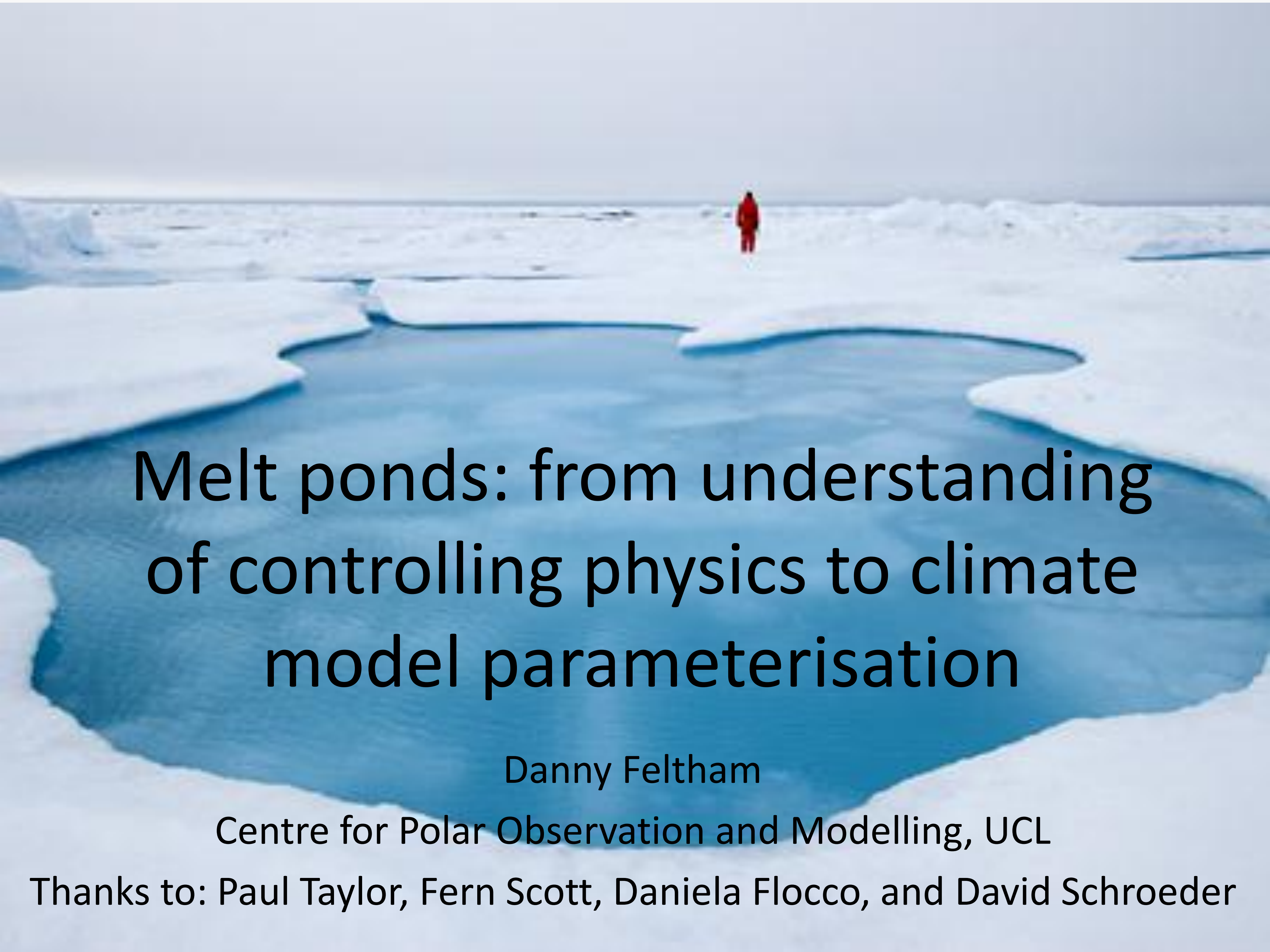


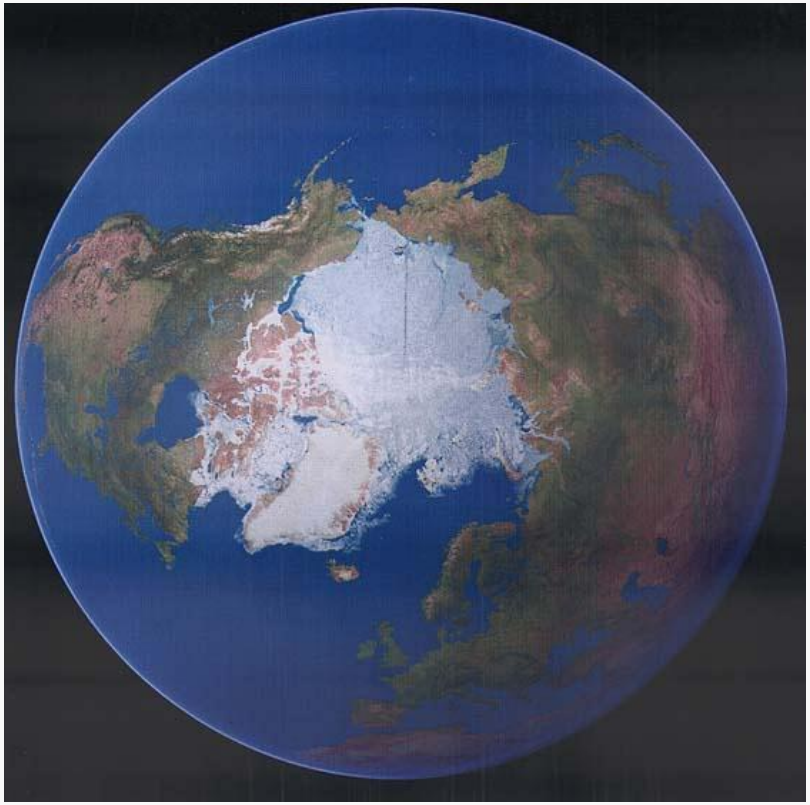
Melt ponds: from understanding of controlling physics to climate model parameterisation

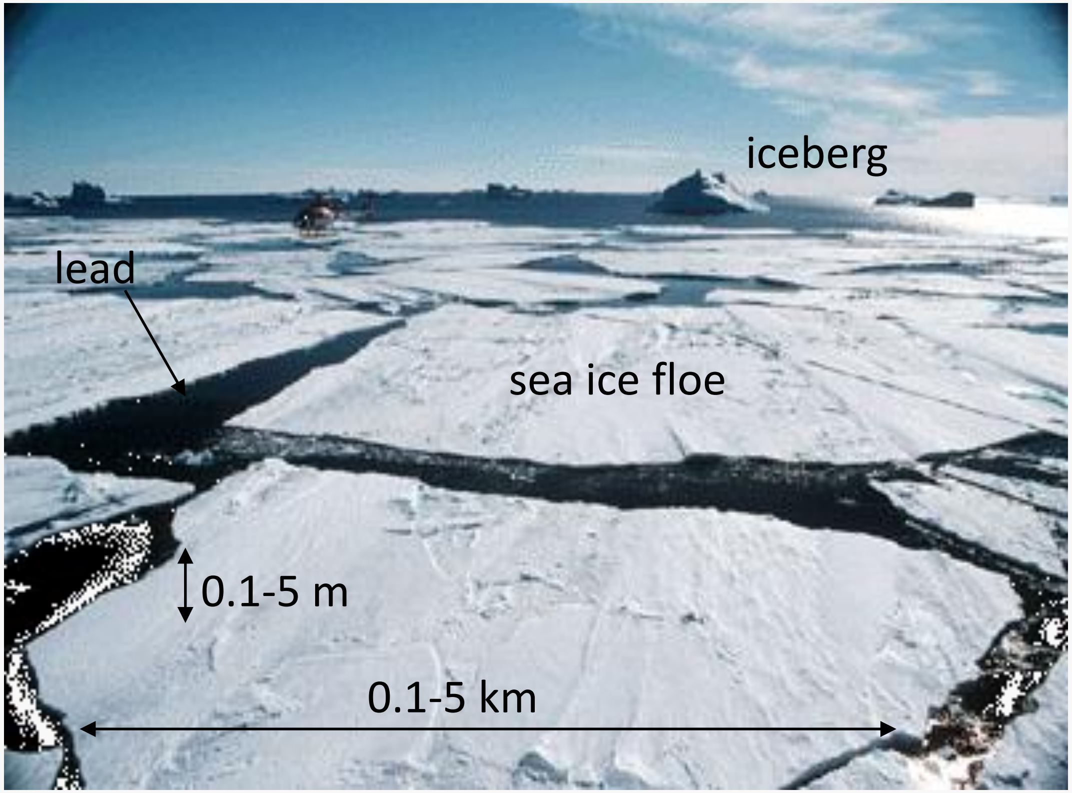
Danny Feltham

Centre for Polar Observation and Modelling, UCL

Thanks to: Paul Taylor, Fern Scott, Daniela Flocco, and David Schroeder

Sea ice





- Sea ice covers approximately 8% of the Earth's oceans at maximum extent.
- Sea ice is a partial barrier to transports of heat, moisture and momentum between the air and ocean.
- Sea ice formation releases salt, and melting releases freshwater; sea ice plays a fundamental role in the global thermohaline circulation.

→ all modern Global Climate Models (GCMs) contain models of sea ice.

What controls the evolution of the sea ice cover?

- **Dynamic** processes control the motion of ice cover, deformation, and redistribution of thickness. Example processes are air and ocean drag, and ice rheology.
- **Thermodynamic** processes control melting, freezing, and dissolving. Example processes are thermal conduction, brine convection, and solar radiation absorption.
- Both dynamic and thermodynamic processes involve **coupled** interactions with the atmosphere and ocean.
- The "amount" of sea ice is determined by an **intimate mixture** of dynamic and thermodynamic processes.

A sea ice lead, formed by mechanical divergence.

- Here, we focus on one particularly important thermodynamic phenomena – the presence and impact of **melt ponds**.

Talk structure

I. Background and motivation

- Sea ice, under-performing climate predictions, melt ponds

II. A model of the vertical evolution of a melt pond

- Mushy layers, radiative models, turbulent ponds

III. A model of the horizontal evolution of melt ponds

- Cellular automata, porous media flow, simulated pond coverage

IV. Bringing it together: melt ponds in GCMs

- Necessary assumptions, initial results

Sea ice is a sensitive indicator of climate change

- Global warming is intensified at the poles by up to a factor of 5 due to the albedo feedback mechanism.

The albedo of a surface is a measure of its reflectivity to incoming radiation (e.g. visible light);

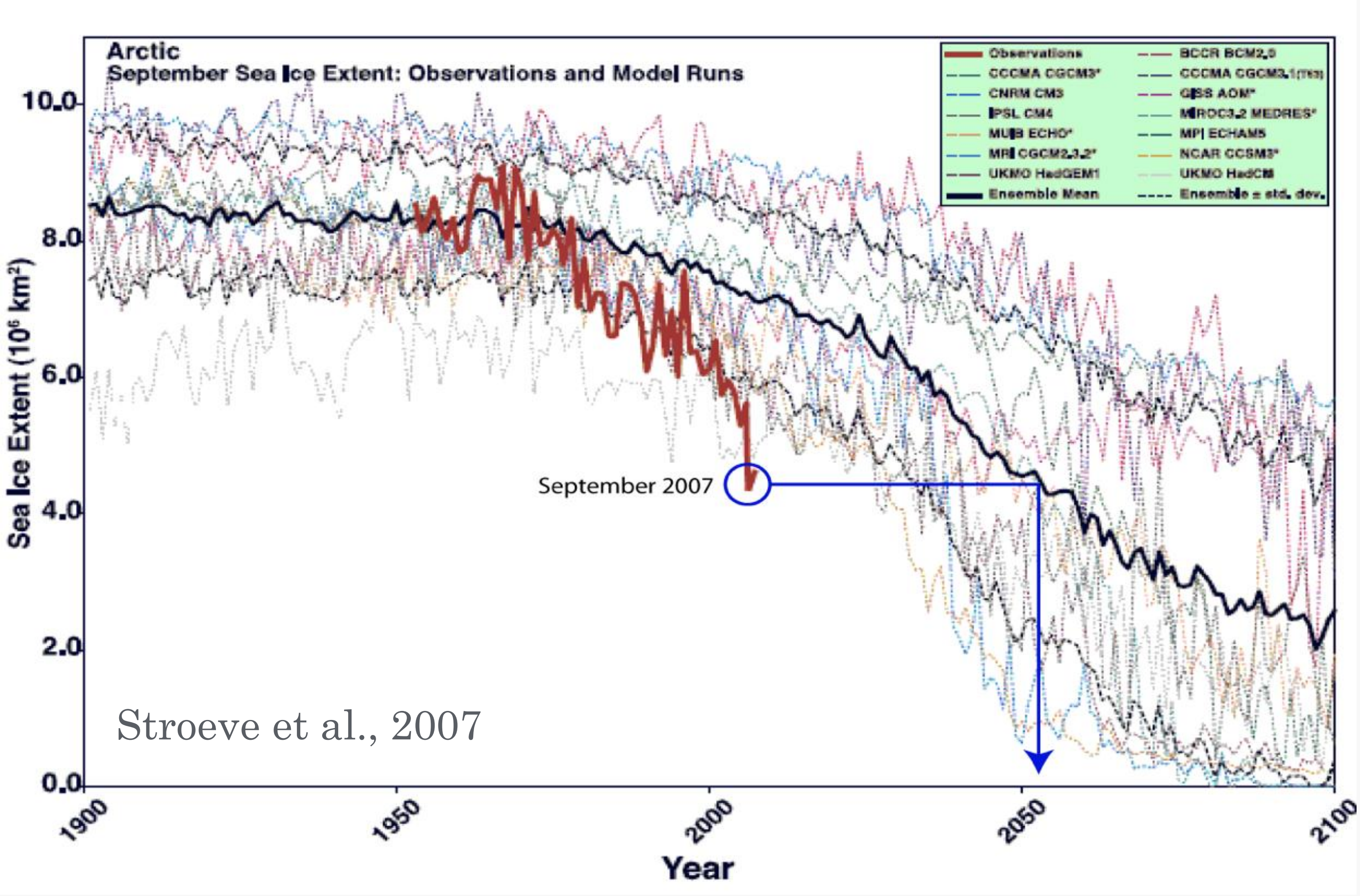
the albedo of ice and snow is much higher than seawater so a reduction in ice/snow cover results in greater absorption of solar radiation;

the absorbed heat can melt ice and snow, reducing the albedo further; and so on…

- Sea ice is expected to respond rapidly to climate change, e.g. the residence time of sea ice in the Arctic Ocean is from 1-10 years.

  (In contrast to the ice sheets of Greenland and Antarctica.)

Rapid reduction of summer Arctic sea ice extent

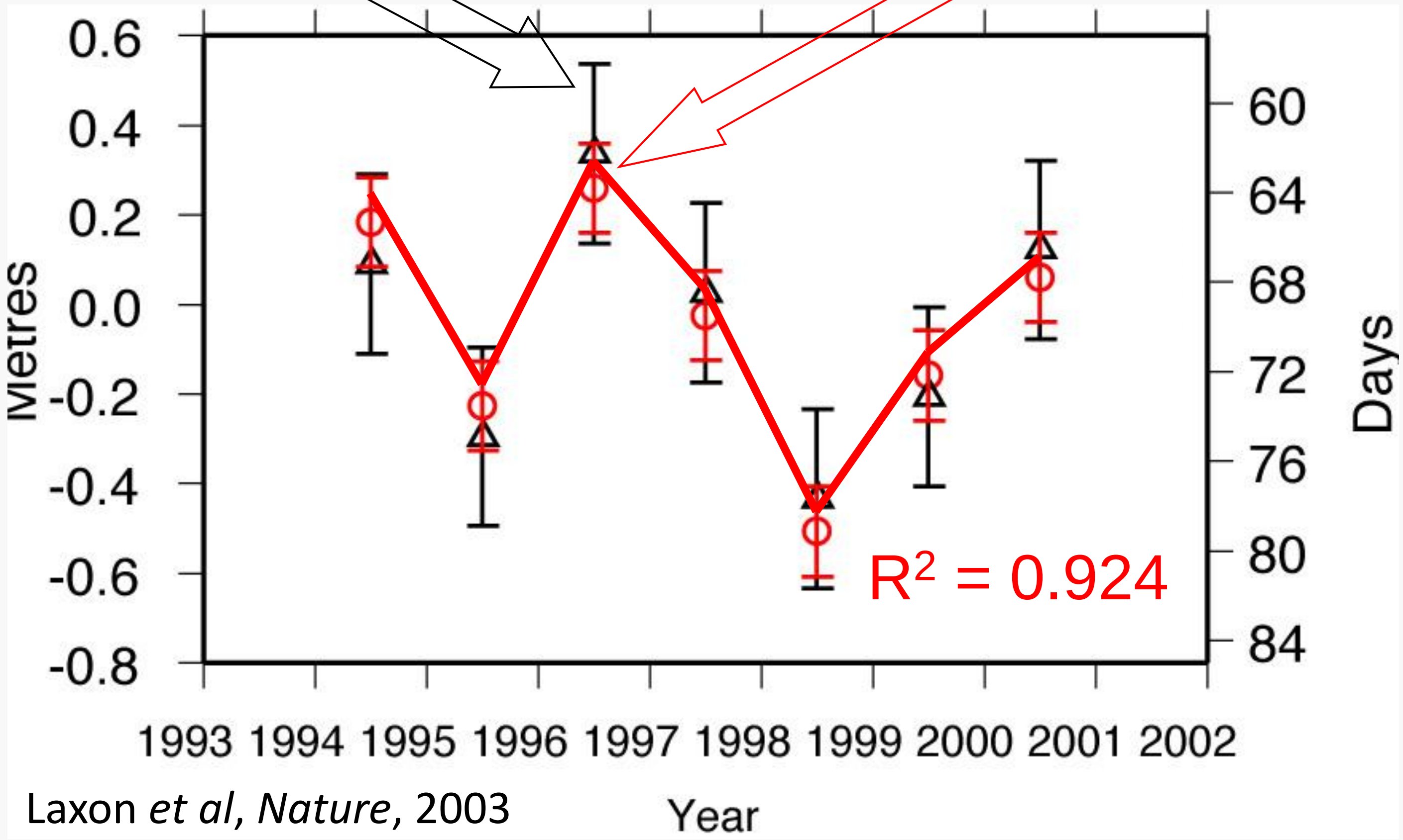


The current generation of GCMs under-predict the loss of Arctic sea ice. <u>Why?</u>

Importance of summer melt processes to sea ice mass balance

Arctic-average winter ice thickness change

Length of preceding summer melt season



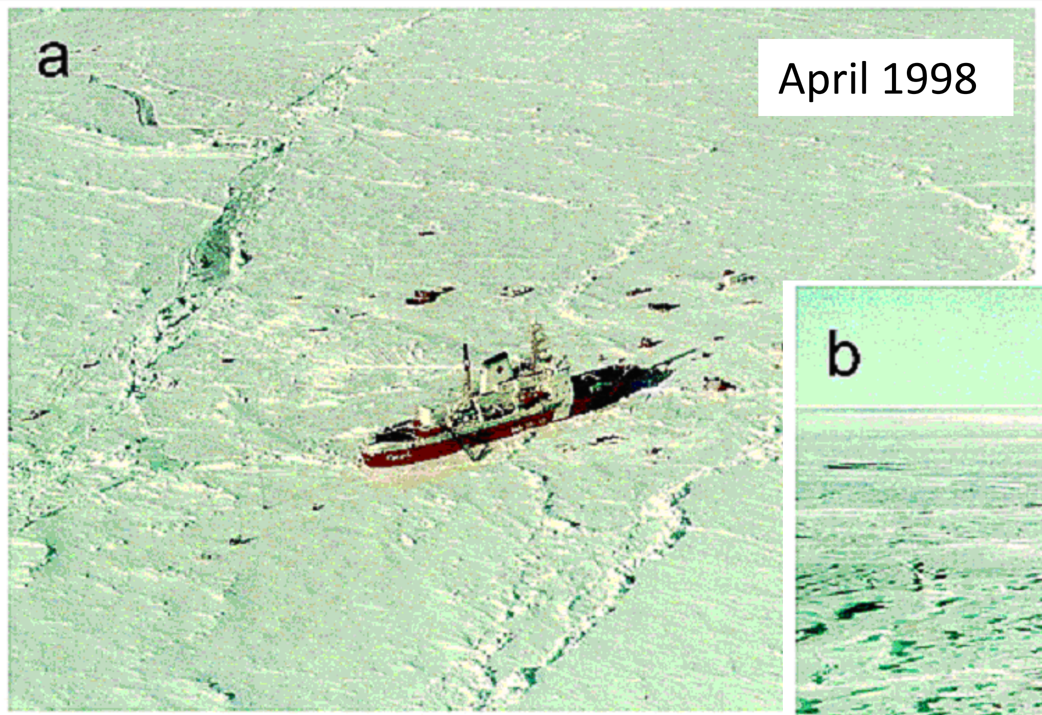
Laxon *et al*, *Nature*, 2003

Using ERS satellite data, strong correlation found between ice thickness and length of previous melt season.

Field observations of summer melting

The SHEBA US field experiment spent a year on the ice (1997/1998), measuring the atmospheric and oceanic forcing of the ice cover and recording the melting processes taking place.

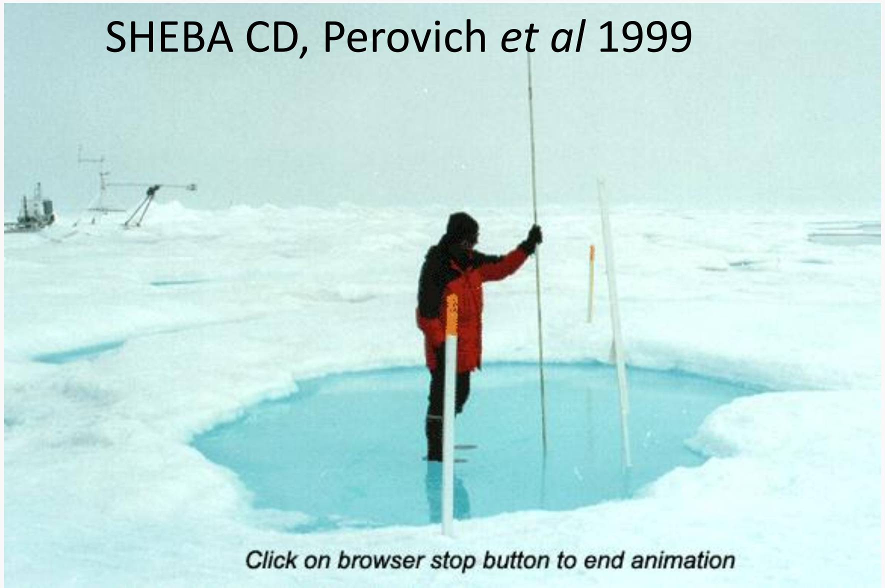
SHEBA field experiment



Ice Station SHEBA. Canadian Coast Guard icebreaker *Des Groseilliers*.

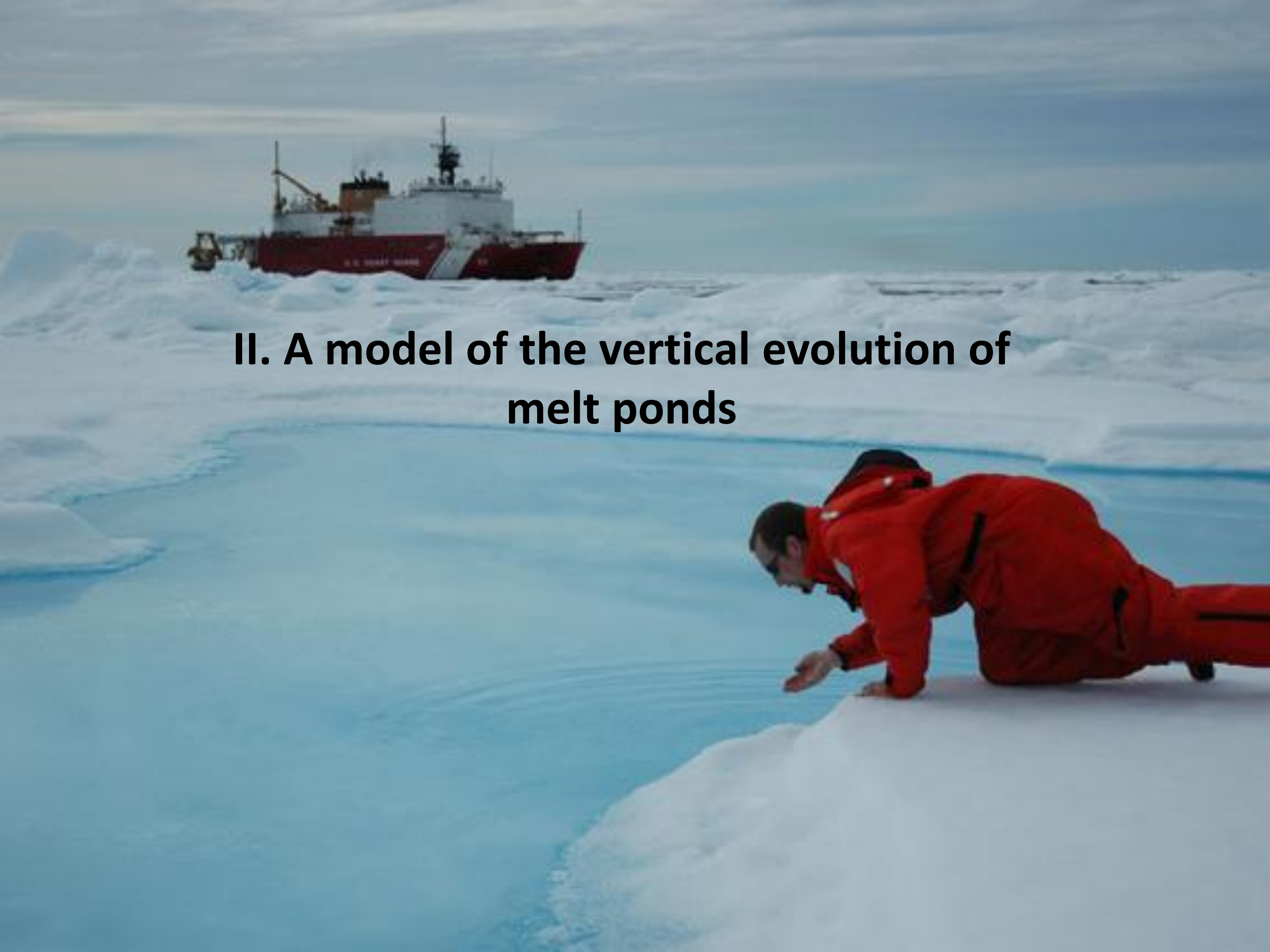
"The story of summer [surface] melting of the Arctic ice cover is the story of melt ponds" Don Perovich, lead scientist of the SHEBA field experiment.

Melt ponds



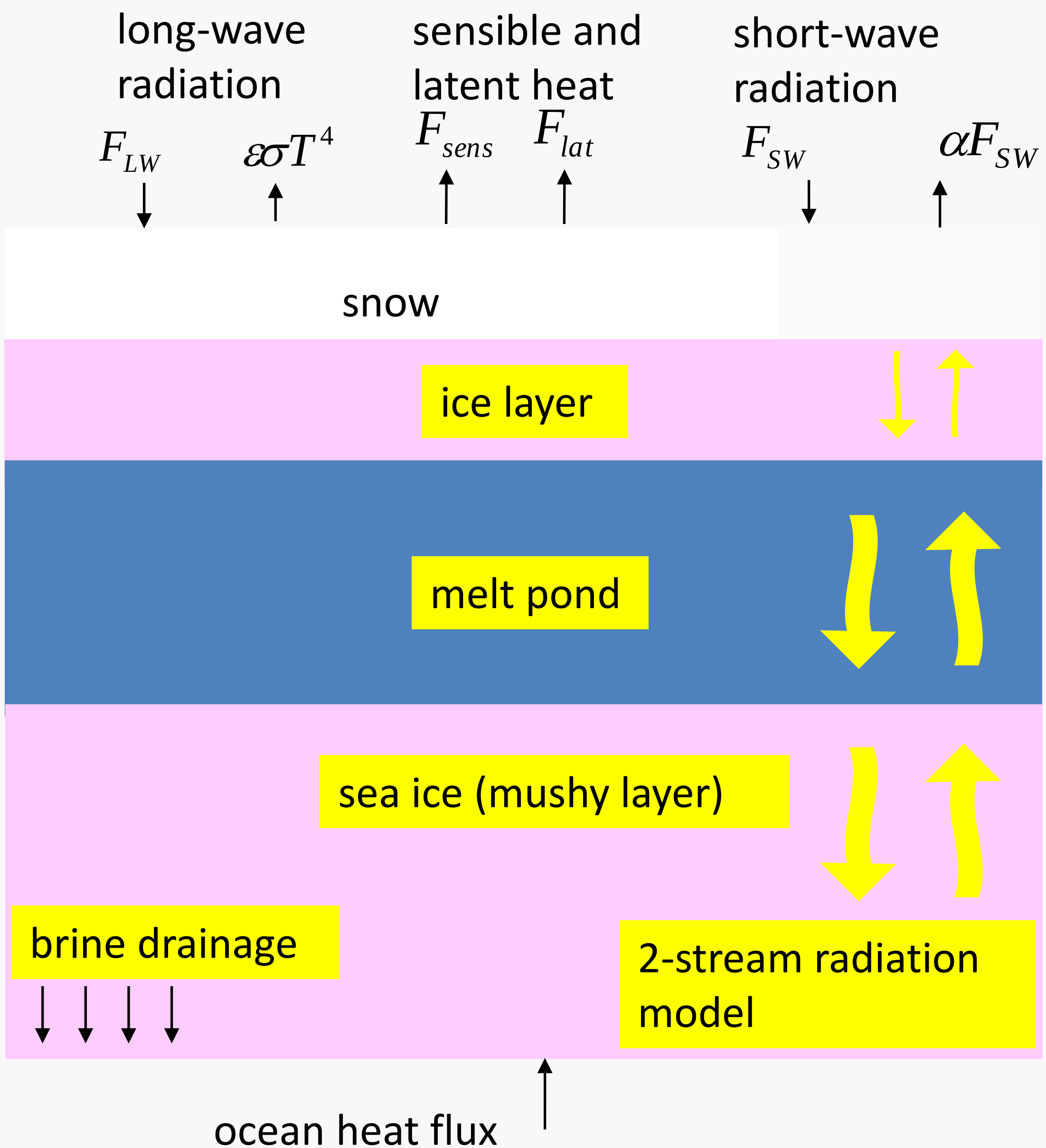
- Surface snow and ice melts due to absorbed solar, short wave radiation and accumulates in ponds
- Pond coverage ranges from 5—50%
- albedo of pond-covered ice < albedo of bare sea ice or snow covered ice
  (0.15—0.45) (0.52—0.87)
- Ponded ice melt rate is 2—3 times greater than bare ice and melt ponds contribute to the albedo feedback mechanism
- **Melt ponds are not explicitly represented in Global Climate Models**

II. A model of the vertical evolution of melt ponds



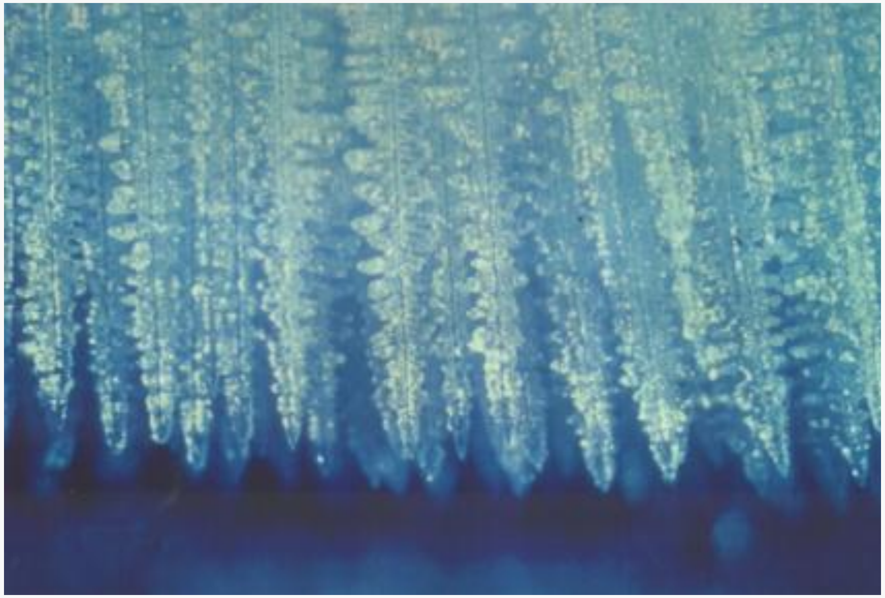
One-dimensional melt pond-sea ice model

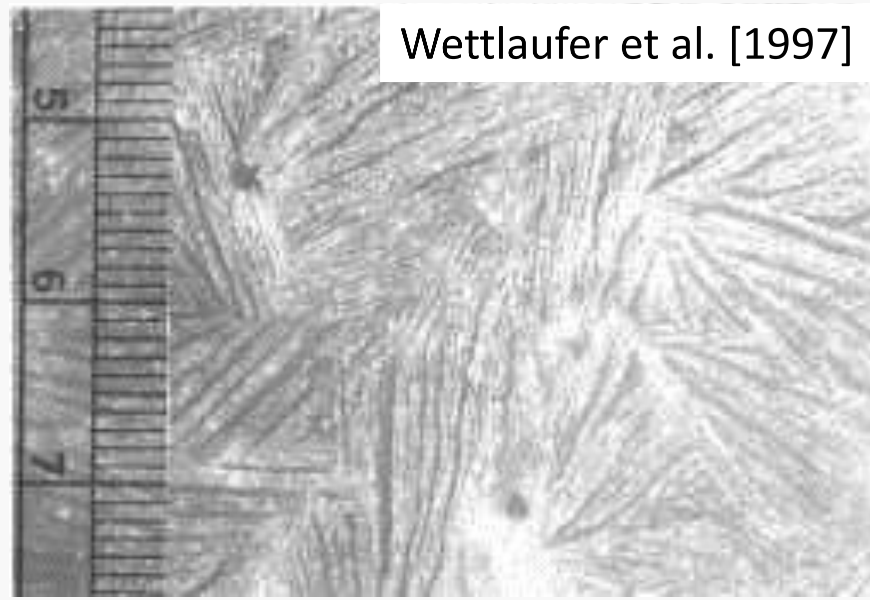
Taylor and Feltham [2004]



- Local heat balance equations in each phase coupled to 2-stream radiative model that allows albedo to be calculated
- Multiple phase combinations, e.g. snow on ice, pond on ice
- Model forced using SHEBA data
- Sensitivity studies performed

Sea ice is a mushy layer





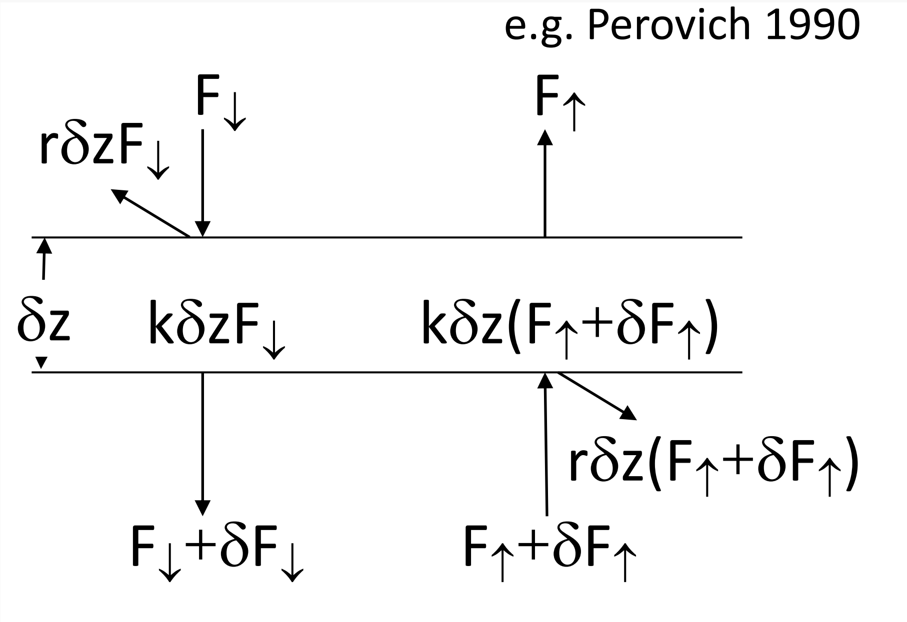
Wettlaufer et al. [1997]

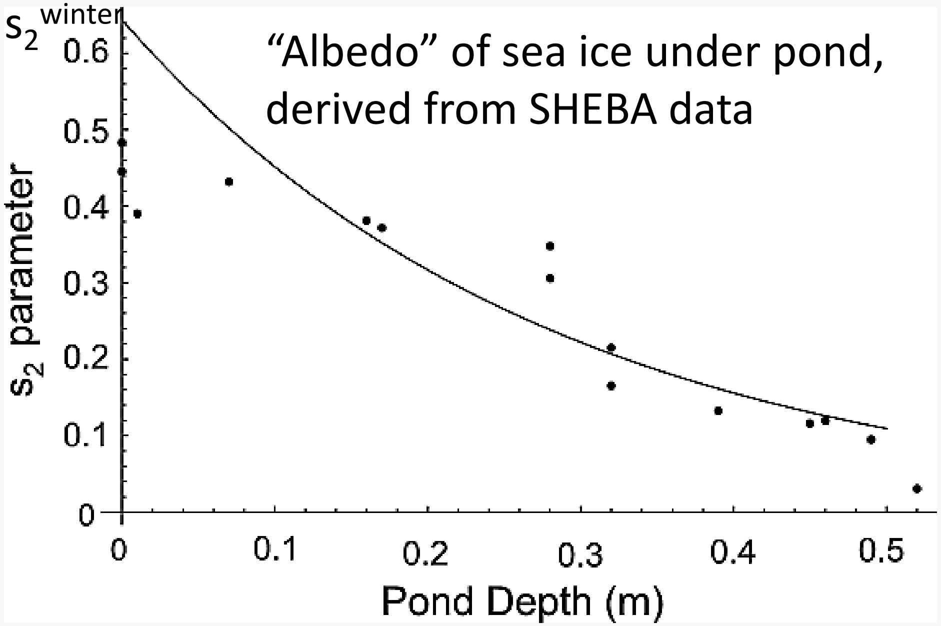
A mushy layer consists of a porous matrix of (almost) pure solid bathed in (highly concentrated) interstitial liquid.

The convoluted geometry enhances expulsion of solute and heat.

Sea ice is an example of a mushy layer, and the mushy layer equations (coupled, nonlinear reaction-advection-diffusion equations) are used for the heat and salt balances [Feltham et al., 2006].

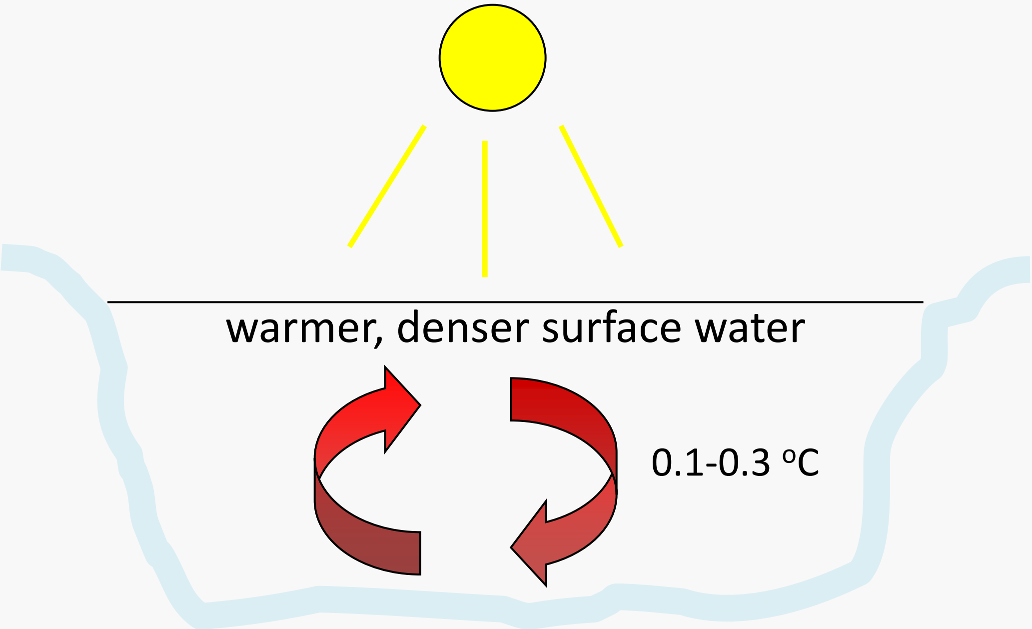
3 layer, 2 stream radiation model





- Irradiance is split into an upwelling $F\uparrow$ and downwelling $F\downarrow$ stream
- Incident radiation is diffuse and scattering is assumed isotropic
- From energy balance perspective, permissible to average over spectral variation [Taylor, 2003]
- Sea ice modelled as one optical layer
- Optical properties of underlying sea ice vary with pond depth

Heat transport in a melt pond



Warm, denser surface waters lead to turbulence once the critical **Rayleigh** number is exceeded:

$$Ra = \frac{g \Delta \rho H^3}{\nu \kappa} > 1101$$

In our model, ponds become turbulent almost as soon as they form.

The heat budget of a turbulent pond is given by

rate of average temperature increase in pond

$$(\rho c)_l h^* \frac{\partial \overline{T}}{\partial t} = -(F_t + F_b) - (F_{net}(h_t) - F_{net}(h_b))$$

heat transported through top and bottom of pond, “4/3” rule

solar radiation absorbed in pond

Example 1D model equations (simplified)

$$F_t + F_{LW} + (1-\alpha_{tot})(1-i_o)F_{SW} - F_{sens} - F_{lat} - \varepsilon\sigma T_0^4 = 0$$

Pond

$$(\rho c)_l h^* \frac{\partial \overline{T}}{\partial t} = -\left(F_t + F_b\right) - \int_{h_b}^{h_t} \frac{\partial F_{net}}{\partial z} dz$$

h*

$$\varphi\rho_s L\left(\frac{dh^*}{dt} - w\right) = F_b - k_m \frac{\partial T}{\partial z} \qquad T = T_L(C_{pond})$$

$$(\rho c)_m \frac{\partial T}{\partial t} + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(k_m \frac{\partial T}{\partial z}\right) + L\frac{\partial\varphi}{\partial t} - \frac{\partial}{\partial z}\left(F_{net}(z,t;h)\right)$$

h

Sea ice

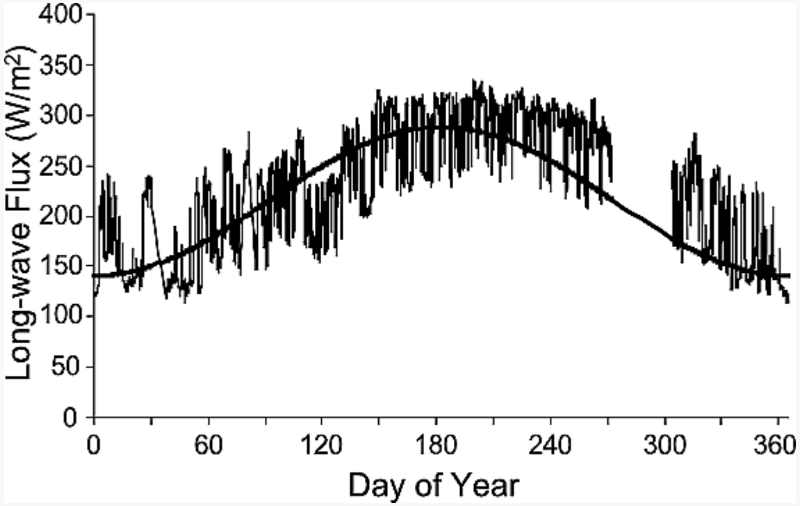
$$(1-\varphi)\frac{\partial C}{\partial t} + w\frac{\partial C}{\partial z} = (C - C_s)\frac{\partial \varphi}{\partial t}$$

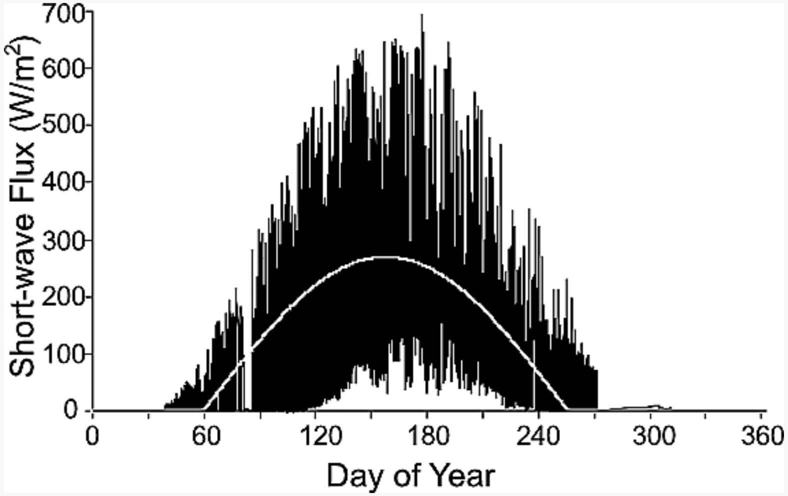
$$T = T_L(C) = -\Gamma C + 273$$

$$\phi\rho_s L\frac{dh}{dt} = k_m\frac{\partial T}{\partial z} - F_{ocean} \qquad T = T_L(C_{ocean})$$

SHEBA forcing data

- Incoming shortwave and longwave radiation
- Air temperature, specific humidity (monthly averaged)
- Constant wind speed at 10 metres



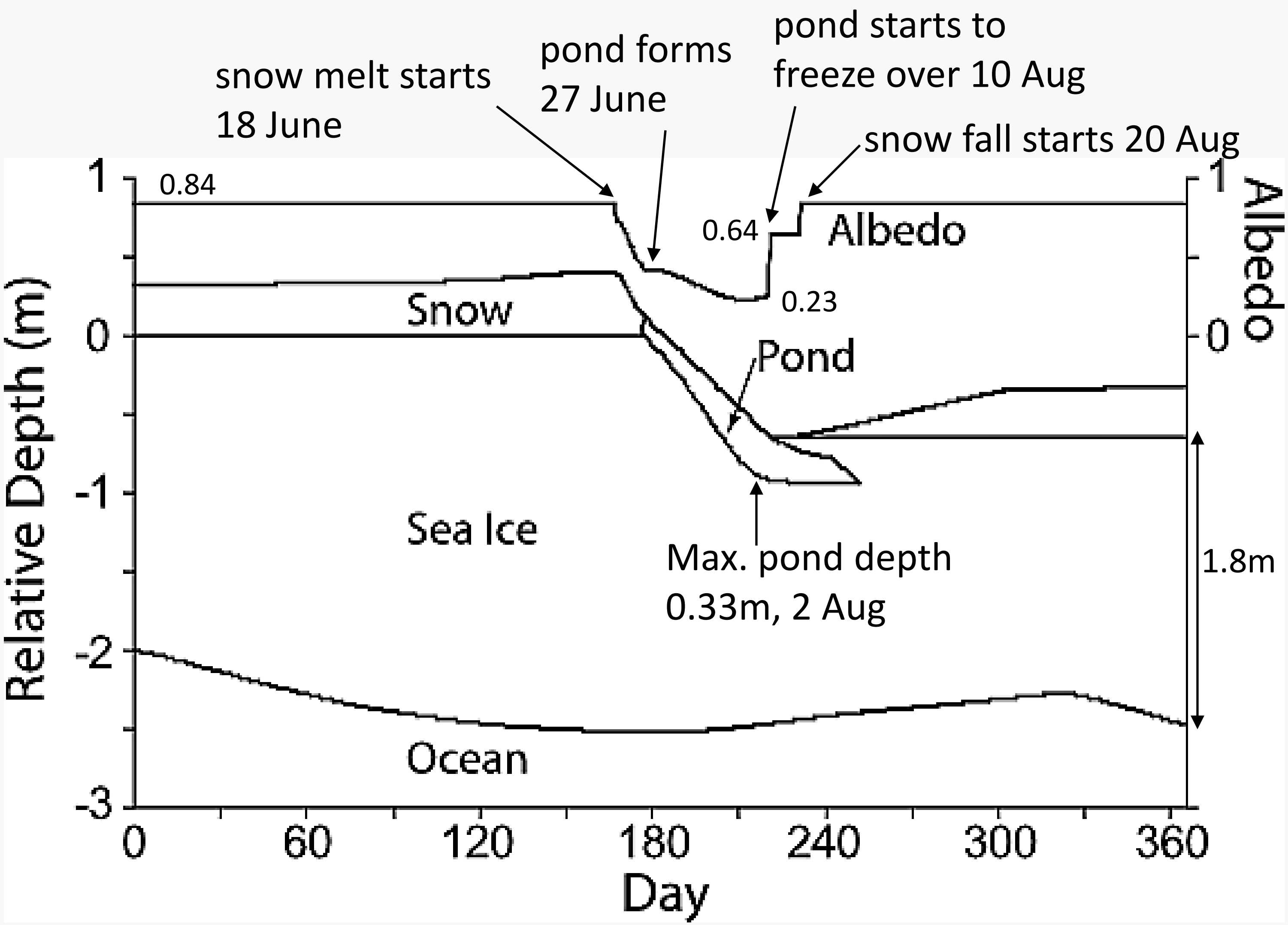


(Averaged over diurnal variation for computational economy.)

- Used a constant ocean heat flux of 2 Wm^{-2}.
- Snow precipitation scheme of Maykut and Untersteiner (1971)

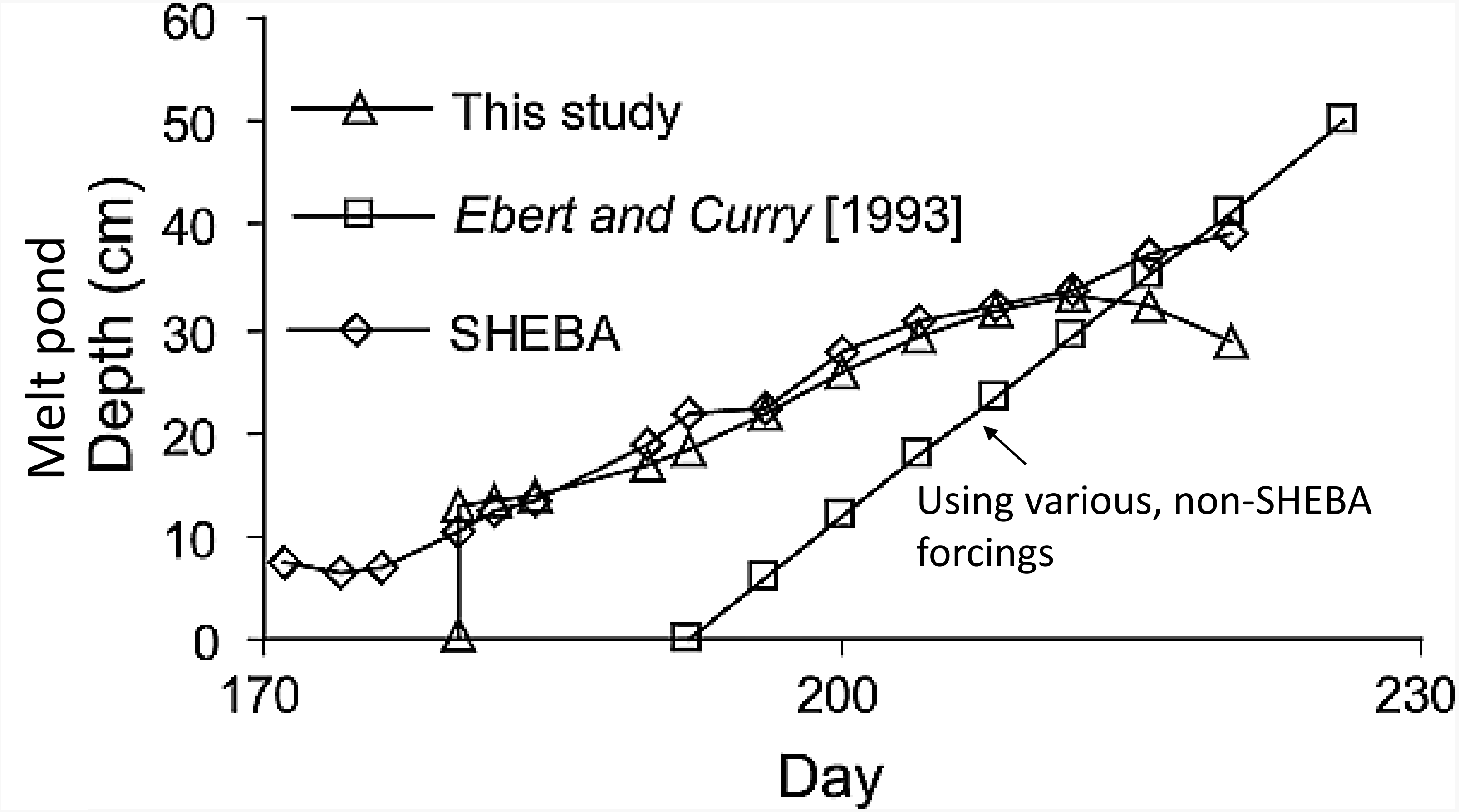
We thank our colleagues in the SHEBA Atmospheric Surface Flux Group, Ed Andreas, Chris Fairall, Peter Guest, and Ola Persson for help collecting and processing the data. The National Science Foundation supported this research with grants to the U.S. Army Cold Regions Research and Engineering Laboratory,
NOAA's Environmental Technology Laboratory, and the Naval Postgraduate School.

Standard run 1/2



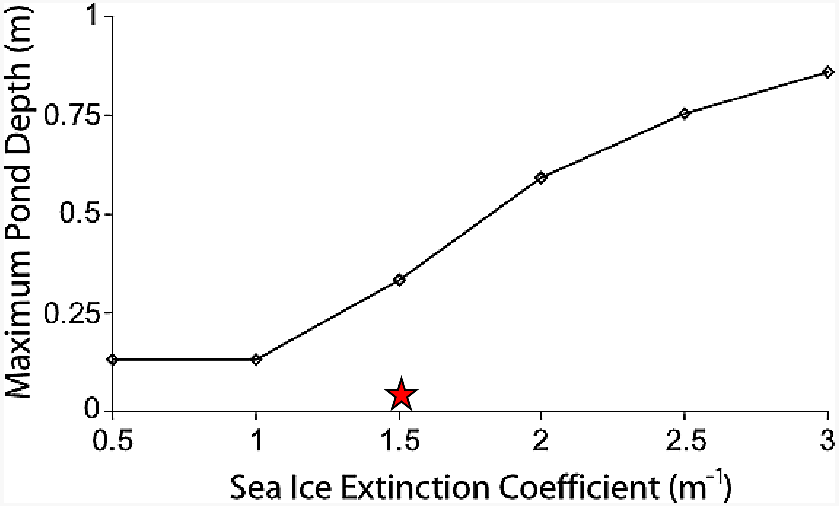
Net drainage over melt season is 0.64 m.

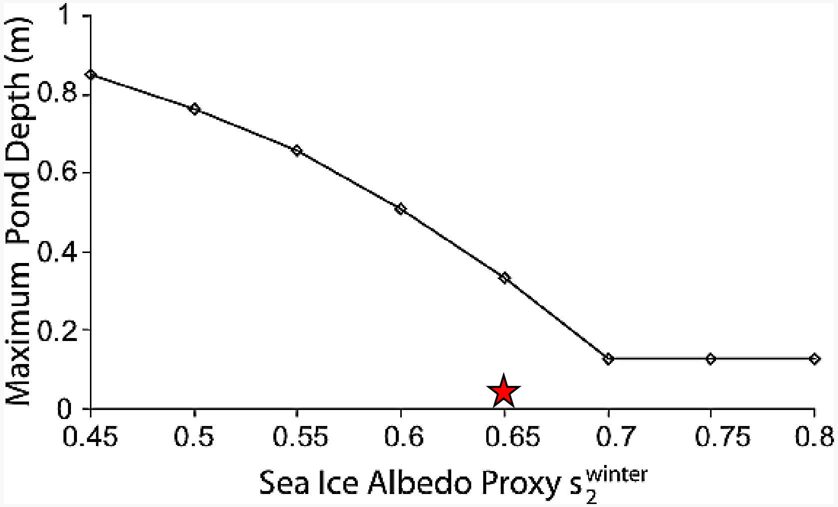
Standard run 2/2

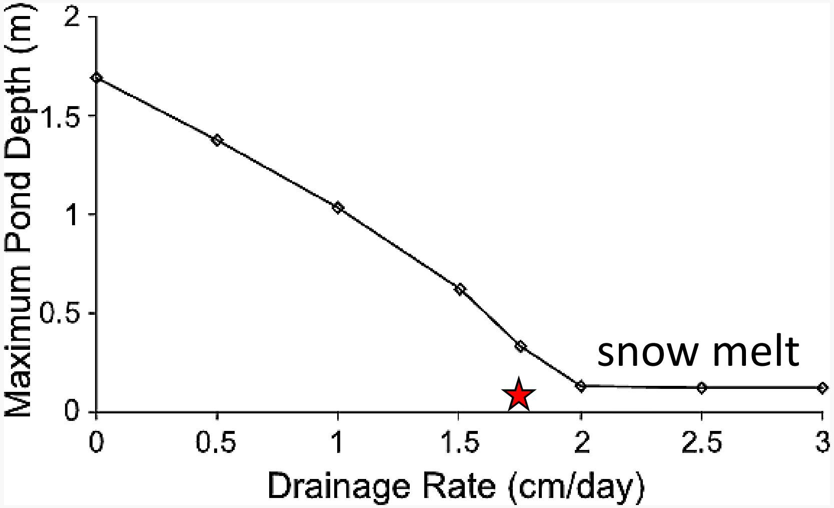


- Standard model run produces realistic behaviour, using SHEBA data.
- Delay in pond formation maybe due to simple snow albedo and/or rain.

Example sensitivity studies

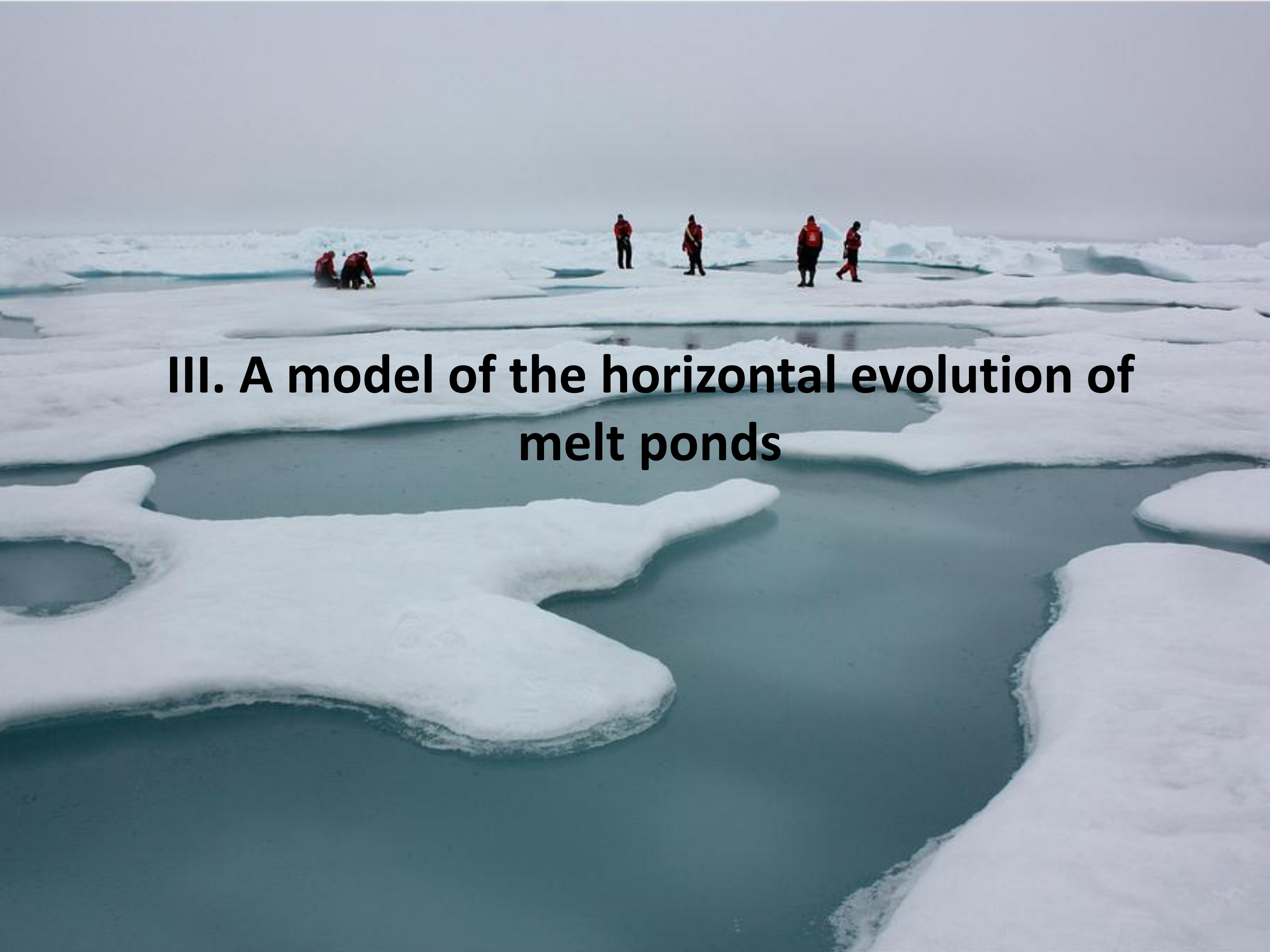






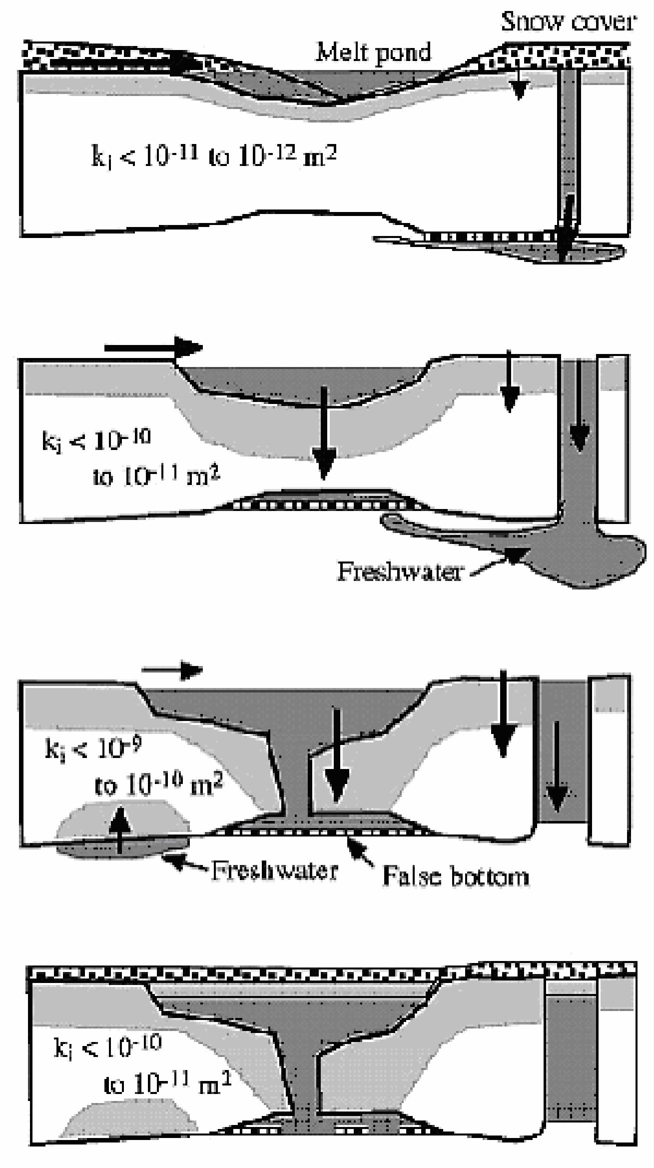
Parameter:	Sensitivity
Drainage	-5.23
Initial ice thickness	0.80
Max. snow depth	3.82
Ice extinction coeff.	2.10
Ice albedo proxy s_2	-7.51
Pond extinction coeff.	0.245
Pond i_0	-9.67

III. A model of the horizontal evolution of melt ponds



Lifecycle of melt ponds

Eicken et al, 2002



Stage I: Snow melt; lateral melt water transport dominate vertical drainage; drainage in flaws; some underwater ice formation

(late May – 20 June)

Stage II: Lateral and vertical melt water transport; reduction of hydraulic head (height of pond above sea level); flaws enlarged; “false bottom”

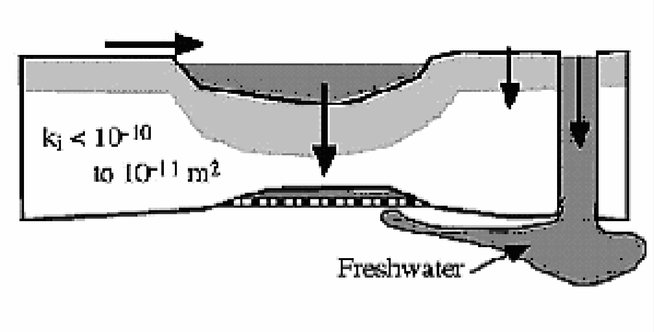
(20 June – 20 July)

Stage III: Lateral and vertical melt water transport; flaws enlarged to point of floe disintegration

(20 July – 10 Aug)

Stage IV: Ponds freeze over; snow fall; bottom melting may continue

Factors affecting horizontal evolution of melt ponds



[Eicken et al, 2002]

Details of local processes very complex, e.g. lens formation, super-imposed ice, false bottoms, etc.

However,… possible to identify important factors:

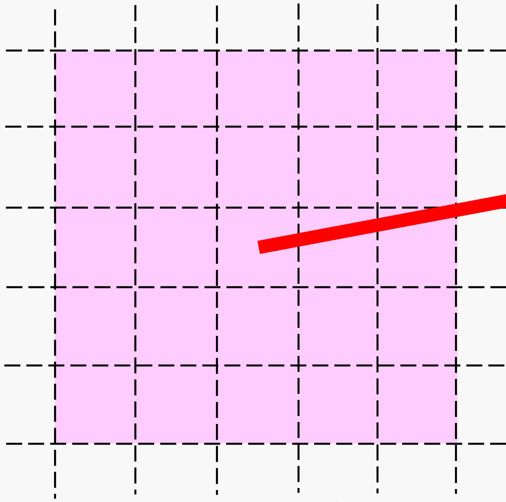
- Snow cover determines where ponds first form (initial source of melt water);
- Meltwater drains horizontally and vertically through the ice;
- Topography of sea ice surface determines where water accumulates.

(Calculations show melting of pond side walls less important than above factors.)

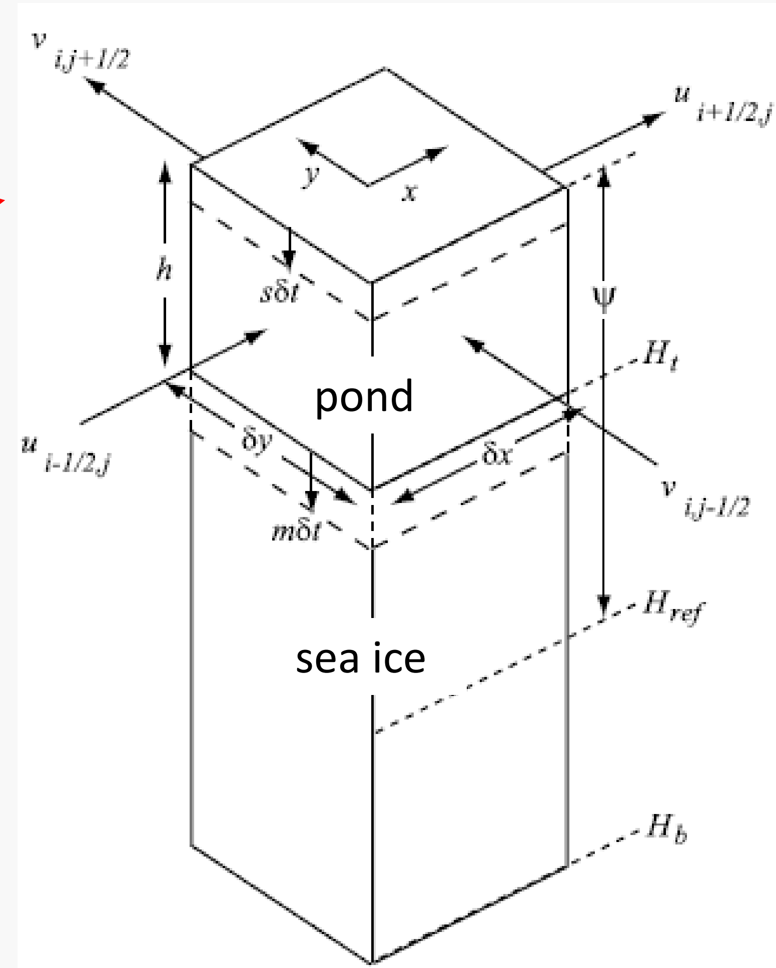
A model of horizontal melt pond evolution 1/2

[Scott and Feltham, 2010; Luthje, Feltham, Taylor and Worster, 2006]

Bird's eye view of sea ice:



vertical section through cell:



- The sea ice cover is split into equal square cells like a checker board

- In time Δt :

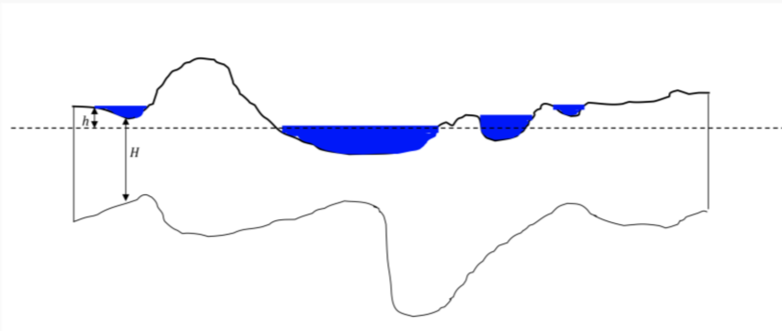
 1) the sea ice/snow in a square melts at a rate *m* calculated from the 1D melt pond/sea ice model;

 2) melt water drains out of the bottom of the cell at a seepage rate *s* calculated from hydraulic head and Darcy's law;

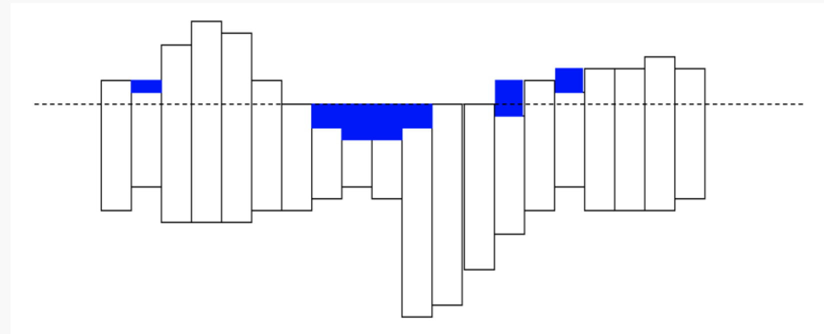
 3) melt water is transported to/from adjacent cells according to Darcy's law with the horizontal pressure gradient determined from the melt water surface topography.

A model of horizontal melt pond evolution 2/2

Profile of sea-ice floe



Profile of sea-ice floe in cellular model



- Sea level calculated by assuming entire floe is in hydrostatic equilibrium
- Drainage rate calculated using Darcy's Law:

$$\mathbf{u} = -\Pi_h \frac{g\rho}{\mu} \nabla h$$

Horizontal transport of melt water

$$w = -\Pi_v \frac{g\rho}{\mu} \frac{\Delta h}{H}$$

Vertical seepage through ice,
Δh is pond height above sea level

$$\Pi_v = 3 \times 10^{-8} (1-\varphi)^3 \ \ \mathrm{m}^2$$

Vertical permeability [Golden et al, 2007],
φ is solid fraction

$$\Pi_h = 10^{-2} \Pi_v$$

Horizontal permeability

Ice and snow topography generated statistically

Model is composed of cells 5mx5m.

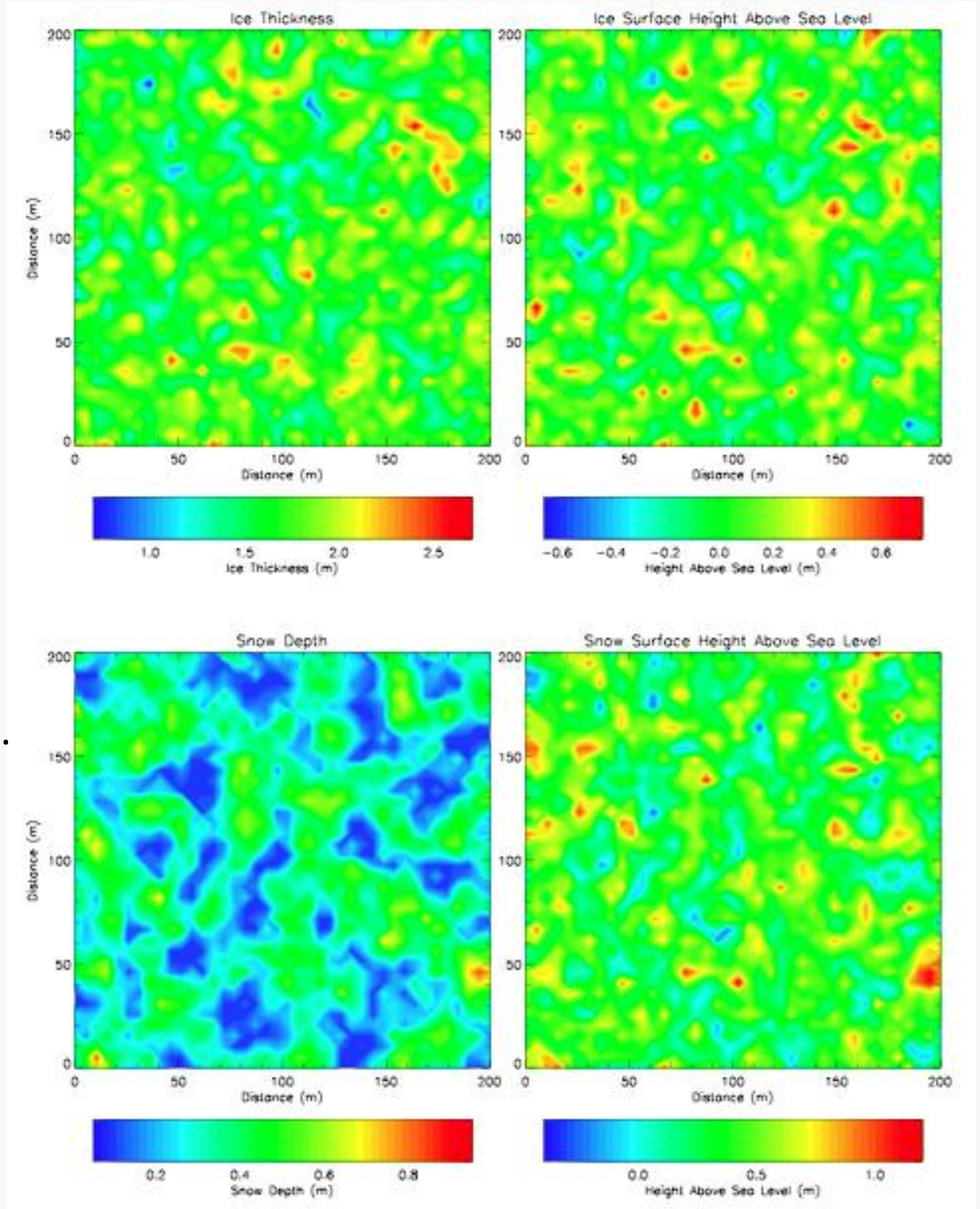
Represent a section of a 200mx200m sea ice floe.

Ice and snow topographies generated using a probabilistic model (with spherical covariance) and by imposing hydrostasy.

Partial data for the model comes from SHEBA measurements [Sturm et al, 2002].

Topography represents “First Year Ice”, i.e. ice that has not yet survived one melt season.

FYI is relatively flat and thin.



Results

Simulation of pond evolution during melt season on First Year Ice using SHEBA observed forcing data.

Edge effects are not modelled (periodic).

$\bar{h}_{ice} = 1.7\text{m}$

$\sigma_{ice} = 0.2\text{m}$

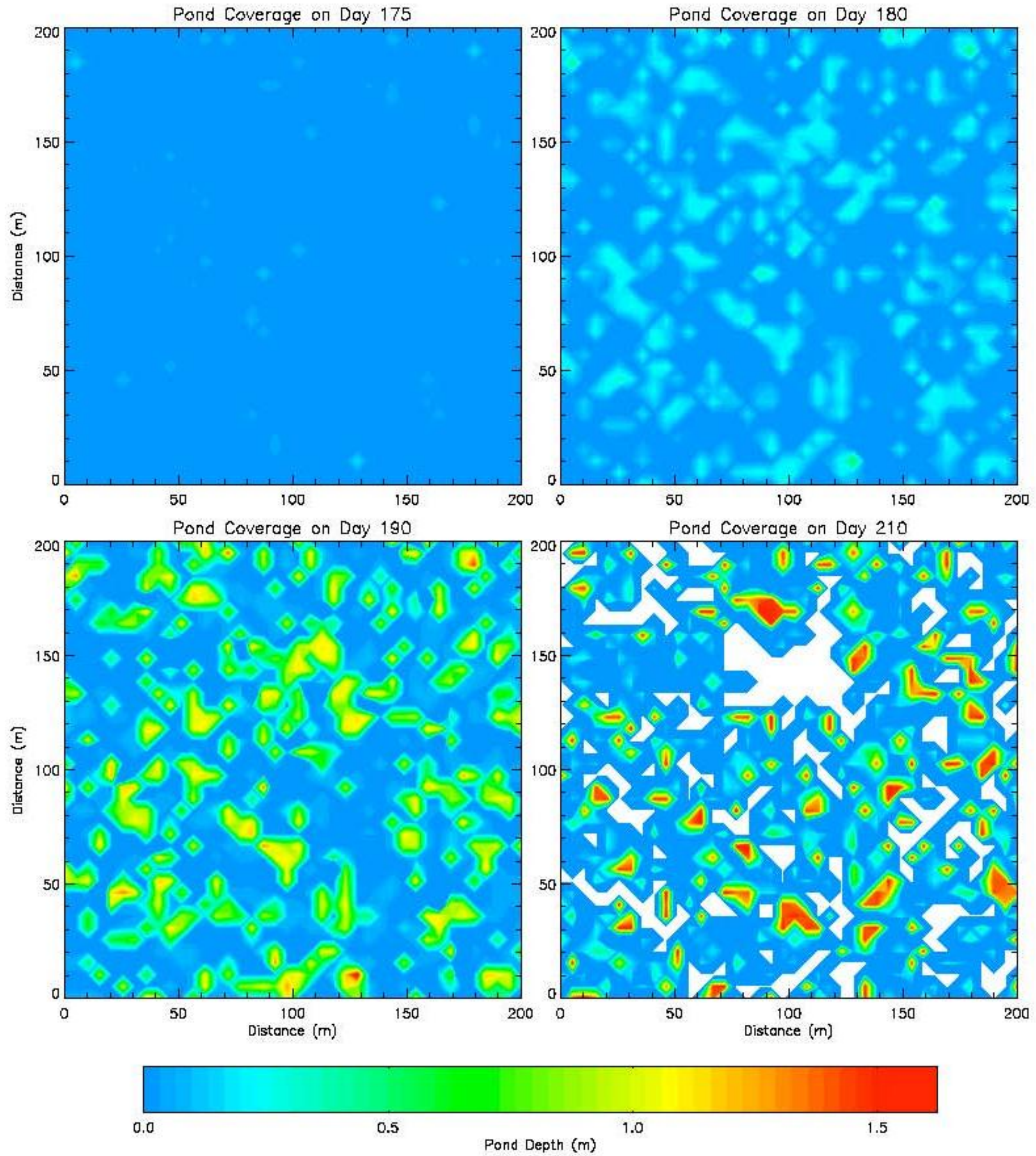
$\text{a}_{\text{ice}} = 10\text{m}$

$\bar{h}_{snow} = 0.3\text{m}$

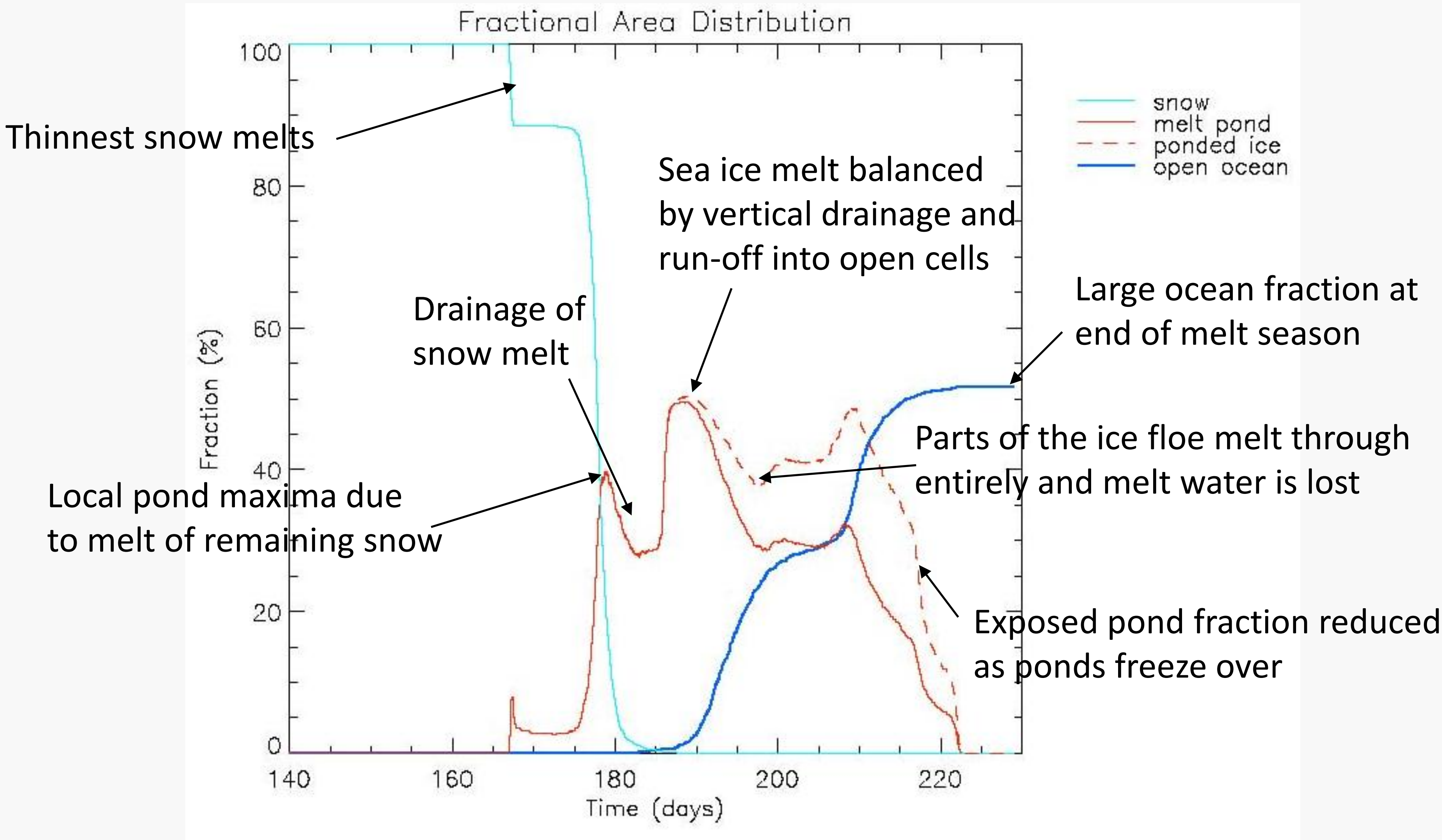
$\sigma_{snow} = 0.15\text{m}$

$\text{a}_{\text{snow}} = 20\text{m}$

White regions have melted through completely.



Standard case First Year Ice



Sensitivity studies

First-year ice model run	Mean Ice Thickness (Standard Deviation) (m)	Mean Snow Thickness (Standard Deviation) (m)	Ice Ablation (m)	Ice and Snow Ablation (m)	Max. Pond Pond Fraction %	Min. Area Averaged Albedo -	Change in Ocean Fraction -
Standard Case	1.70 (0.20)	0.31 (0.15)	1.01	1.33	49	0.32	0.51
Thick Snow	1.70 (0.20)	0.50 (0.15)	1.62	2.15	94	0.09	0.95
Thin Snow	1.70 (0.20)	0.24 (0.15)	0.87	1.10	38	0.37	0.40
Rough Snow	1.70 (0.20)	0.34 (0.25)	1.07	1.45	54	0.30	0.56
Smooth Snow	1.70 (0.20)	0.30 (0.10)	1.00	1.31	48	0.32	0.49
Rough Ice	1.70 (0.50)	0.30 (0.15)	1.12	1.44	56	0.24	0.59
Smooth Ice	1.70 (0.02)	0.30 (0.15)	0.39	0.70	50	0.46	0.08
High Permeability	1.70 (0.20)	0.31 (0.15)	0.96	1.28	44	0.34	0.45
Low Permeability	1.70 (0.20)	0.31 (0.15)	1.53	1.84	91	0.12	0.89

Multi-year ice model run	Mean Ice Thickness (Standard Deviation) (m)	Mean Snow Thickness (Standard Deviation) (m)	Ice Ablation (m)	Ice and Snow Ablation (m)	Max. Pond Pond Fraction %	Min. Area Averaged Albedo -	Change in Ocean Fraction -
Standard Case	2.50 (1.10)	0.30 (0.25)	1.41	1.74	47	0.37	0.36
Thick Snow	2.50 (1.10)	0.60 (0.25)	1.37	1.98	48	0.38	0.37
Thin Snow	2.50 (1.10)	0.20 (0.25)	1.42	1.68	45	0.34	0.35
Rough Snow	2.50 (1.10)	0.30 (0.40)	1.41	1.81	46	0.36	0.38
Smooth Snow	2.50 (1.10)	0.30 (0.10)	1.39	1.68	49	0.36	0.33
Rough Ice	3.40 (1.50)	0.30 (0.25)	1.67	1.73	47	0.31	0.33
Smooth Ice	2.50 (0.50)	0.30 (0.25)	1.23	1.82	53	0.36	0.30
High Permeability	2.50 (1.10)	0.30 (0.25)	1.42	1.76	43	0.31	0.30
Low Permeability	2.50 (1.10)	0.30 (0.25)	1.61	1.95	70	0.19	0.57

Various sensitivity studies have been performed, exploring commonly observed combinations of ice thickness, ice roughness, snow thickness and snow roughness.

We also examined sensitivity to model parameters such as permeability and optical properties of ice, snow and meltwater (scattering and absorption coefficients).

Some highlights

- Simulations agree with field data, e.g. Eicken et al. (2004), El Naggar et al, (1998), Fetterer and Untersteiner (1998) and Yackel et al (2000).

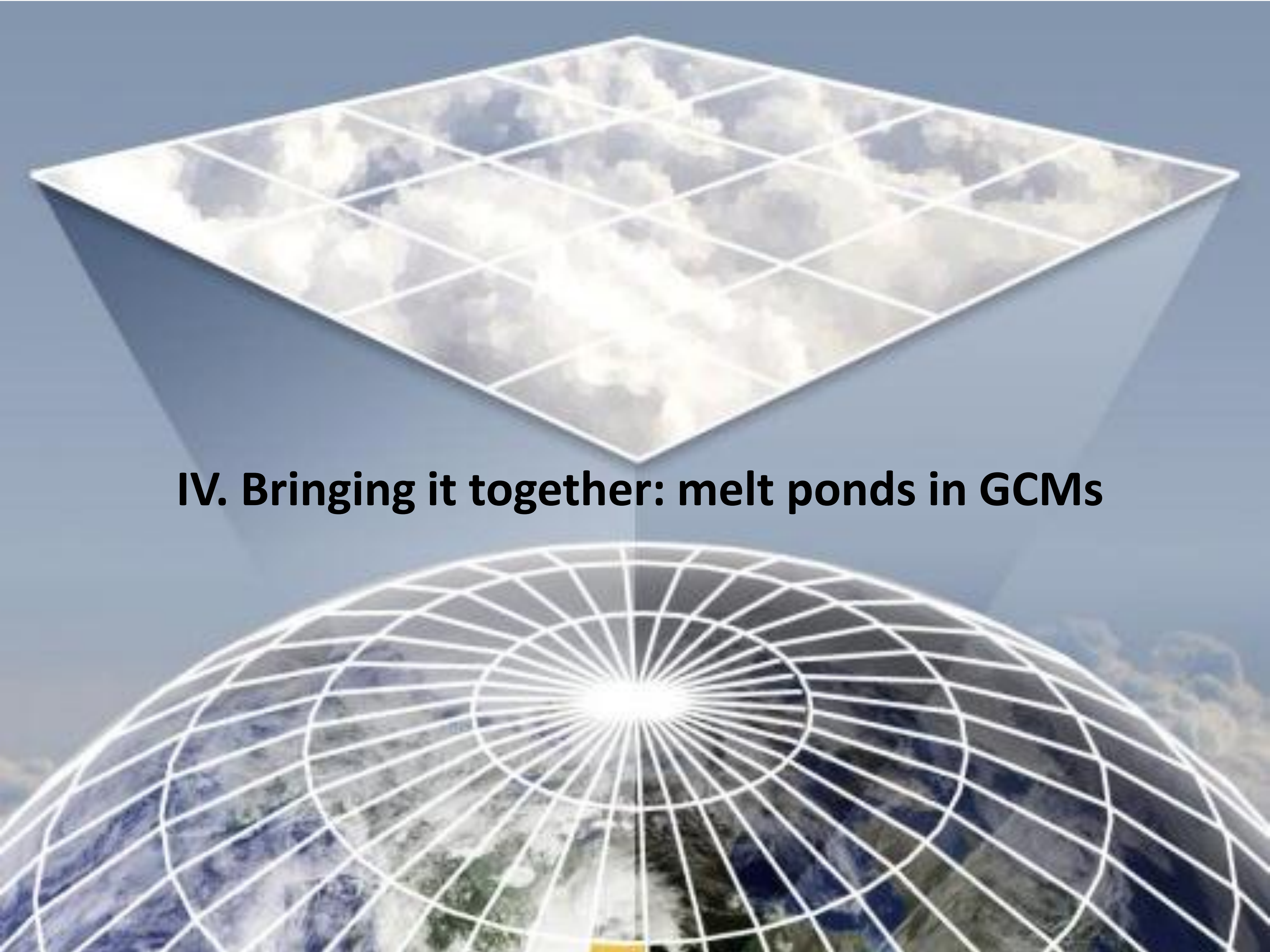
- Pond coverage fairly **insensitive** to snow topography.

- Pond coverage **sensitive** to snow thickness, e.g. increasing initial mean snow thickness from **0.3 m** to **0.5 m** caused an **increase** of total ablation of **1 m** due to the albedo feedback mechanism.

- Flatter ice has a **larger** pond area, but with **reduced** pond depth.

- Contribution of melt ponds to albedo feedback is **stronger** on flatter ice, because of greater pond area, and leads to **greater** total ablation.

IV. Bringing it together: melt ponds in GCMs



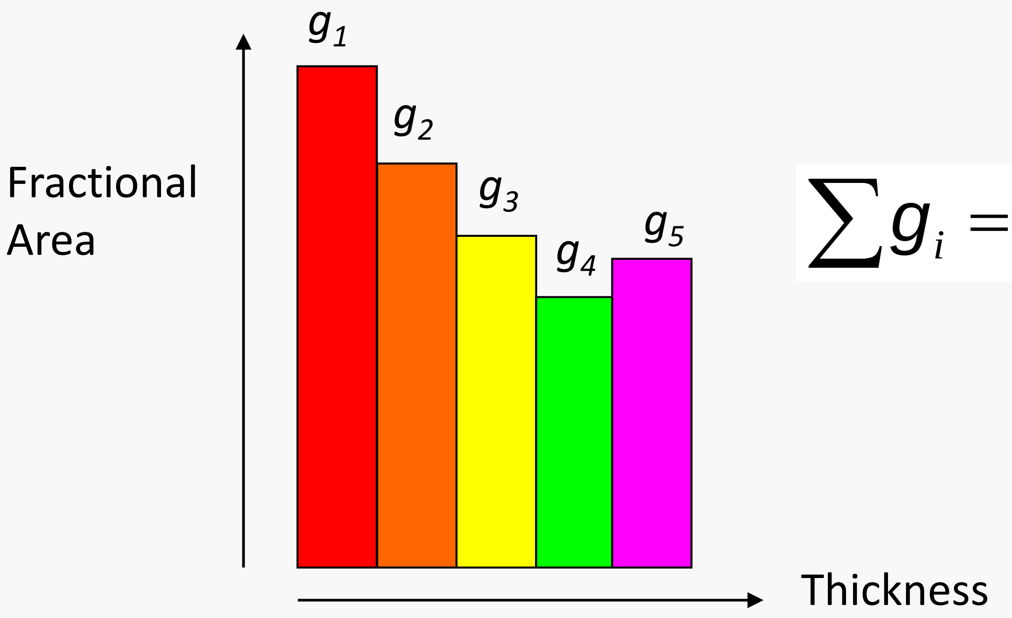
GCM-compatible melt pond model

[Flocco and Feltham, 2007]

Requirements of constructing a melt pond model for use in existing Global Climate Models places strong constraints on the form the model can take.

Main difficulty is that GCMs do not determine the sea ice topography.

Modern GCMs contain a thickness distribution function *g(h).*



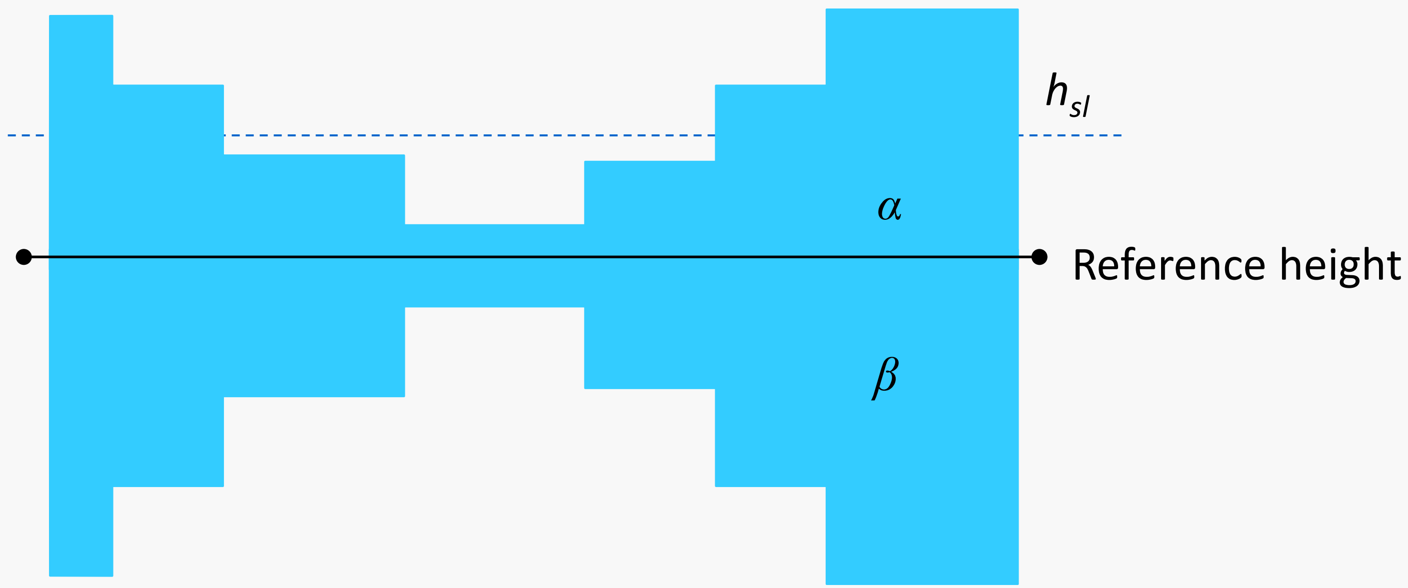
$$\sum g_i = 1$$

Height and depth distribution functions

To redistribute surface water, we need information about the surface height.

We introduce surface height α*(h)* and basal depth β*(h)* distributions,
which give the relative area of ice of a given surface height or basal depth.

We derive α*(h)* and β*(h)* from the thickness distribution *g(h)*.



NOTE: α*(h)* and β*(h)* **do not** describe the topography.

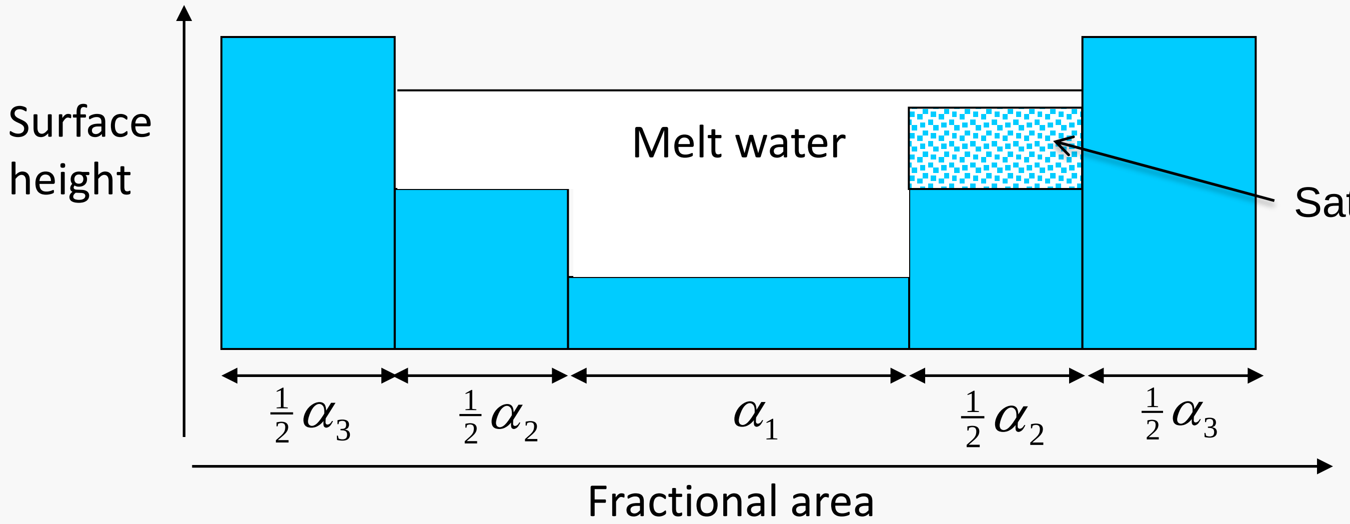
Horizontal redistribution of meltwater

ASSUMPTION: Any point on the ice cover is surrounded by ice of all surface heights, with the relative fraction of ice of given height given by the surface height distribution α*(h)*.

→ Given the presence of ice of all surface heights, surface melt water will tend to collect on ice of the lowest surface height.

ASSUMPTION: Melt water is transported laterally to the lowest surface height within one timestep of a GCM model.

→ Surface meltwater "fills up" the surface, covering ice of lowest height first.

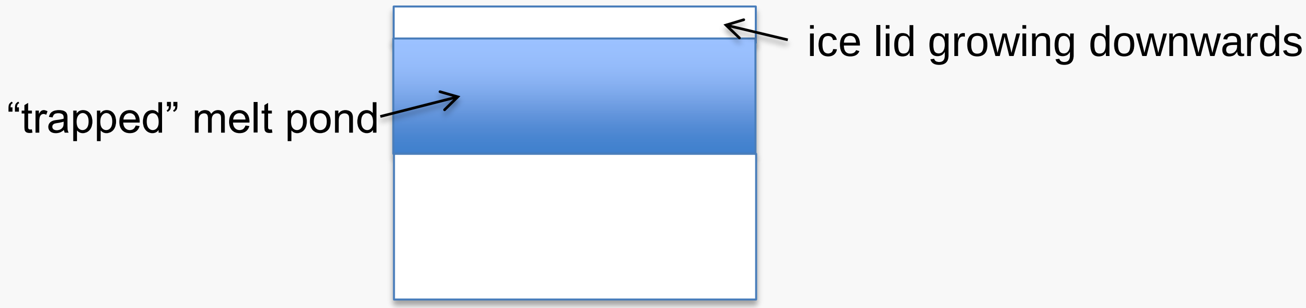


Melt pond parameterisation features

[Thanks to Elizabeth Hunke]

- Pond volume collects on ice of lowest height.
- Hydrostatic balance is maintained throughout.
- Vertical drainage is by Darcy's law with a variable permeability.

- Melt water is lost during ridging.
- Melt water is transported as a tracer on each thickness class.
- During refreezing, a pond lid forms that grows/melts at each time step. Once the pond is completely refrozen, the ice may/may not be transferred to the ice category.



Incorporation of melt pond model into CICE

[Flocco, Feltham, and Turner, 2010; Schroeder, Flocco, Feltham, in progress]

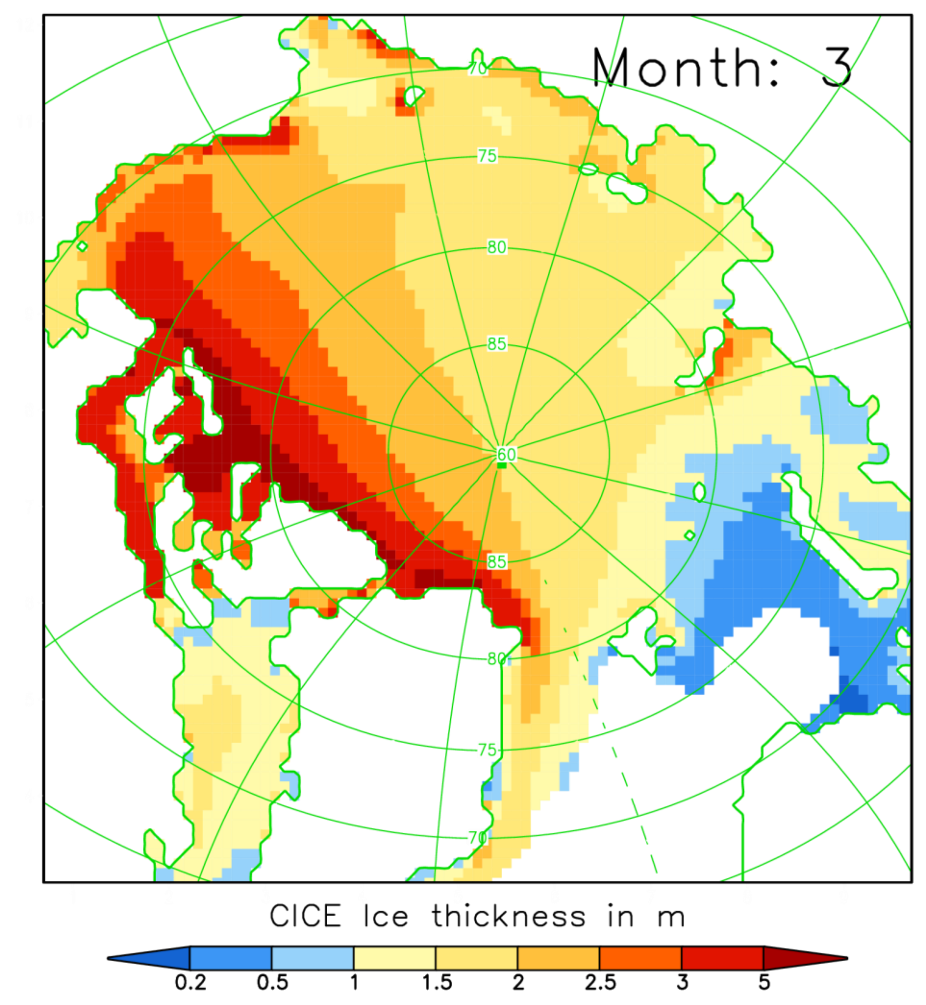
- Melt pond routine incorporated into CICE v. 4.1 and uses the Delta-Eddington radiation scheme.

CICE is the sea ice component of several IPCC climate models.

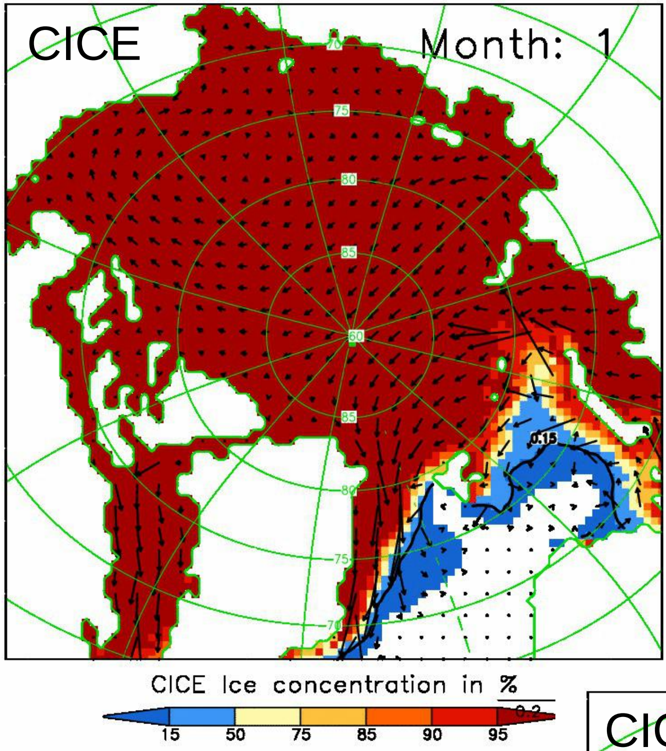
- We run CICE in stand-alone mode.

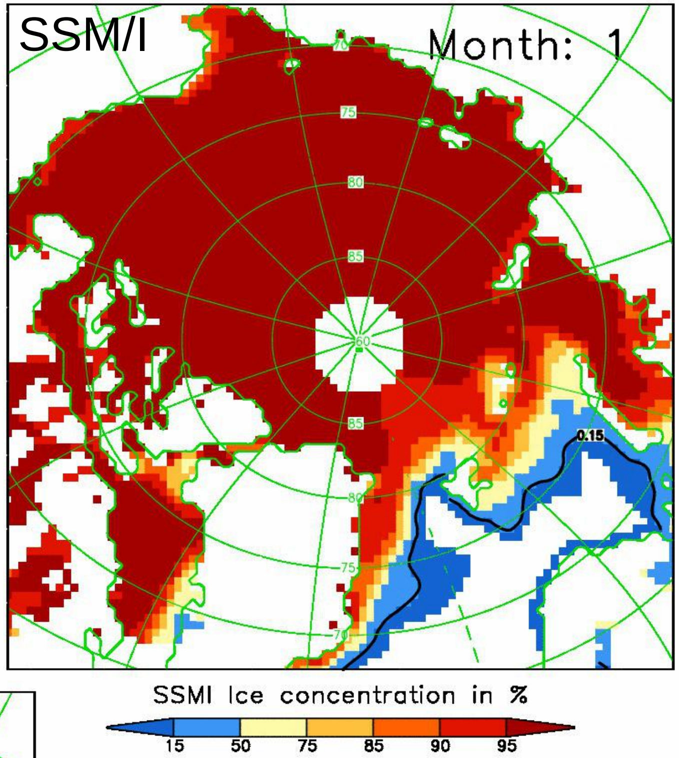
Forcing data:
Atmosphere: DRAKKAR with OMIP corrected SW fluxes;
Ocean: CCSM3 reanalysis deep ocean heat fluxes (monthly climatology);
Other ocean forcing from MyOcean reanalysis (monthy climatology).

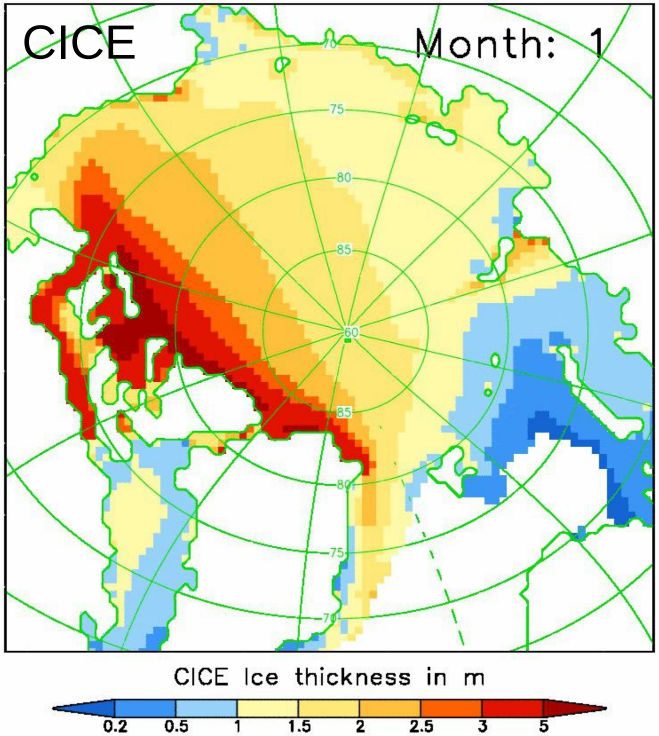
- Model is spun up from 1980-1989, analysed from 1990-2007.



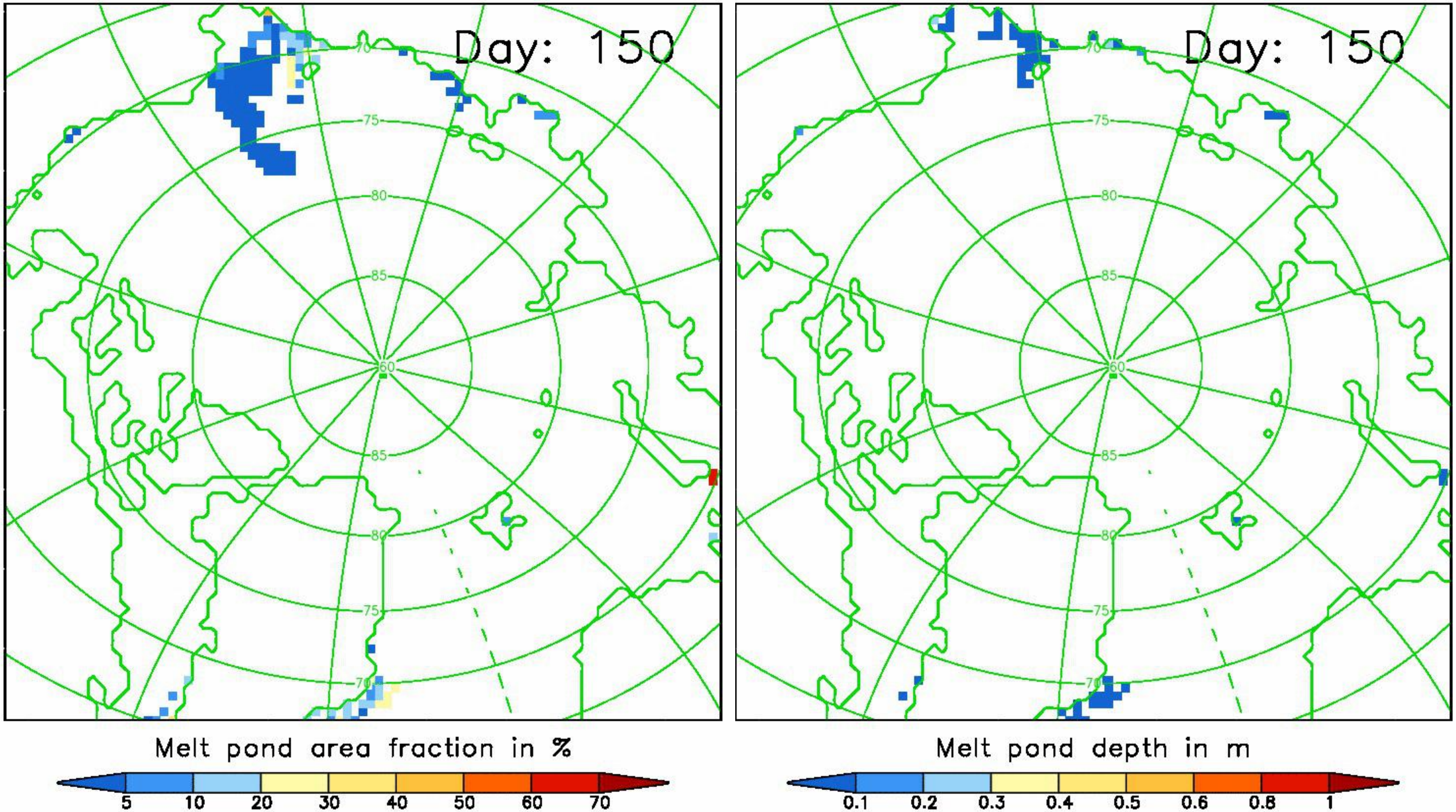
Climatology, 1990-2007

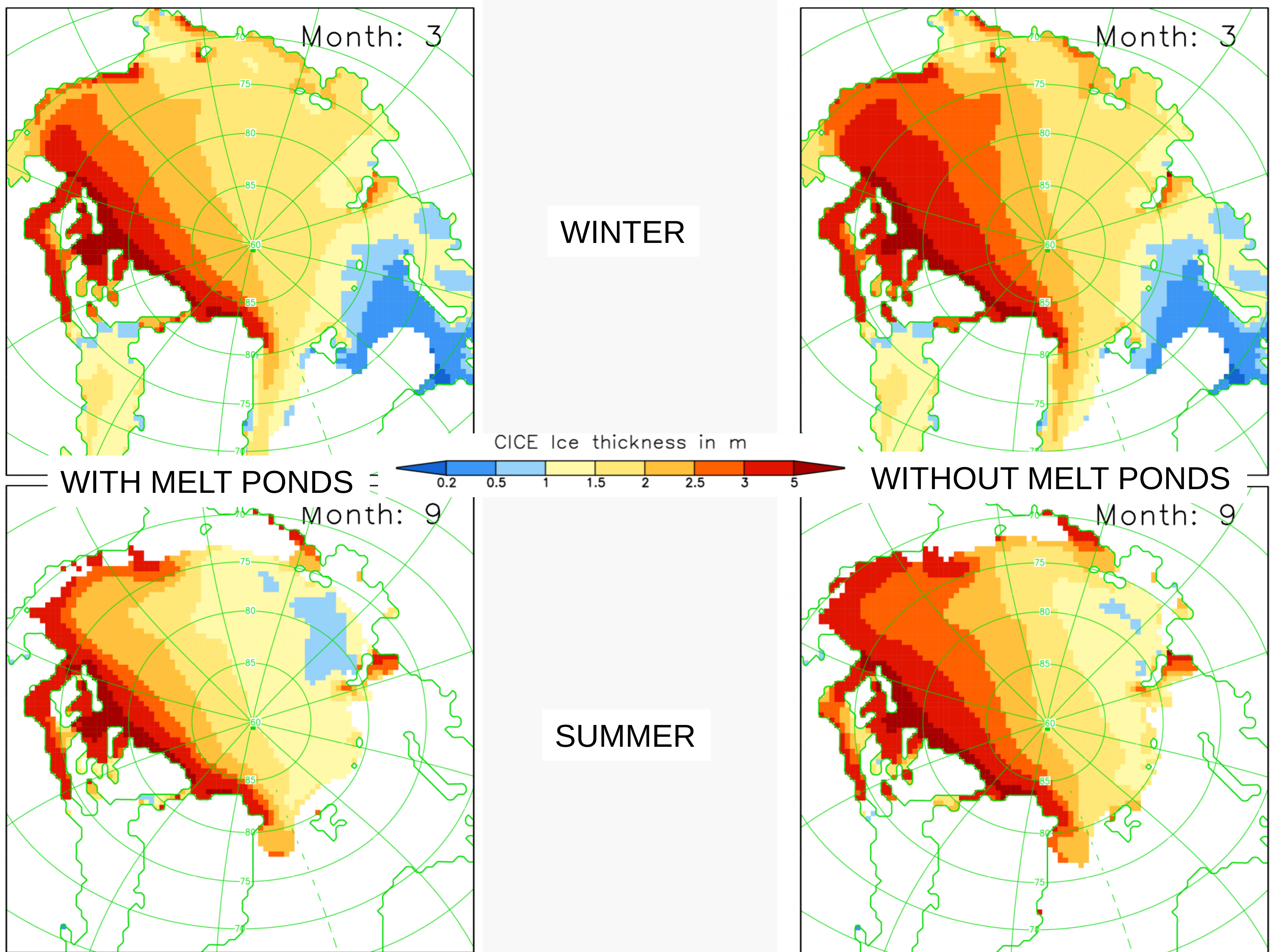






Melt pond area and depth
30th May (Day 150) – 18th August (Day 230) 2007





Month: 3
WINTER
Month: 3
CICE Ice thickness in m
0.2
0.5
1
1.5
2
2.5
3
5
WITH MELT PONDS
WITHOUT MELT PONDS
Month: 9
SUMMER
Month: 9

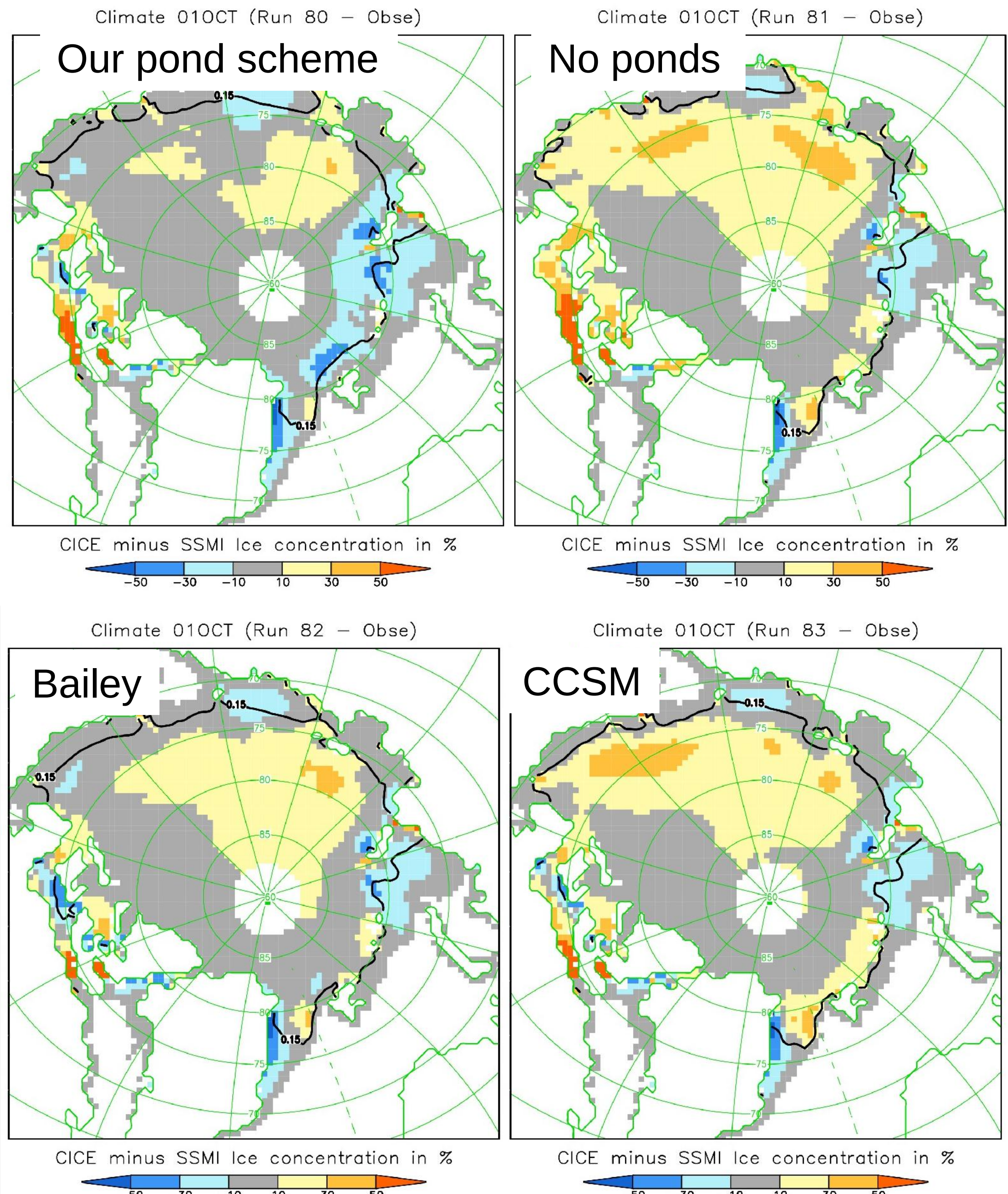
Climatological September ice concentration: CICE minus SSM/I

- Including ponds improves model match with SSM/I.

- Our pond scheme, which is <u>not tuned</u> does a similar job to empirically-tuned melt pond schemes (Bailey, CCSM).

- An advantage of our model is that it can account for future changes in ice cover type (e.g. more FYI).

- Including surface melt water allows a more realistic treatment of the vertical heat budget in the future.



Closing remarks

- Climate models under-predict the rate of decay of Arctic sea ice.
- Satellite observations demonstrate ice cover is highly sensitive to summer melting of sea ice cover.
- Field observations show summer Arctic sea ice surface melt is dominated by melt ponds.

- Idealised mathematical modelling of melt ponds in 1D and 2D has shed insight into the controlling physics and agrees with field observations.
- Models show that melt pond coverage is highly sensitive to ice topography, snow thickness, and optical properties of sea ice.

  In particular, flatter ice has a higher pond coverage and a lower albedo.
- New melt pond model for GCMs allows more realistic simulations of melting of the Arctic sea ice cover in the future.

- The fraction of First Year Ice, which is flatter, is increasing.
- **This suggests that melt ponds will play an increasingly important role in the melting of the Arctic ice cover.**

July 4, 2010: Arctic sea ice and melt ponds in the Chukchi Sea.