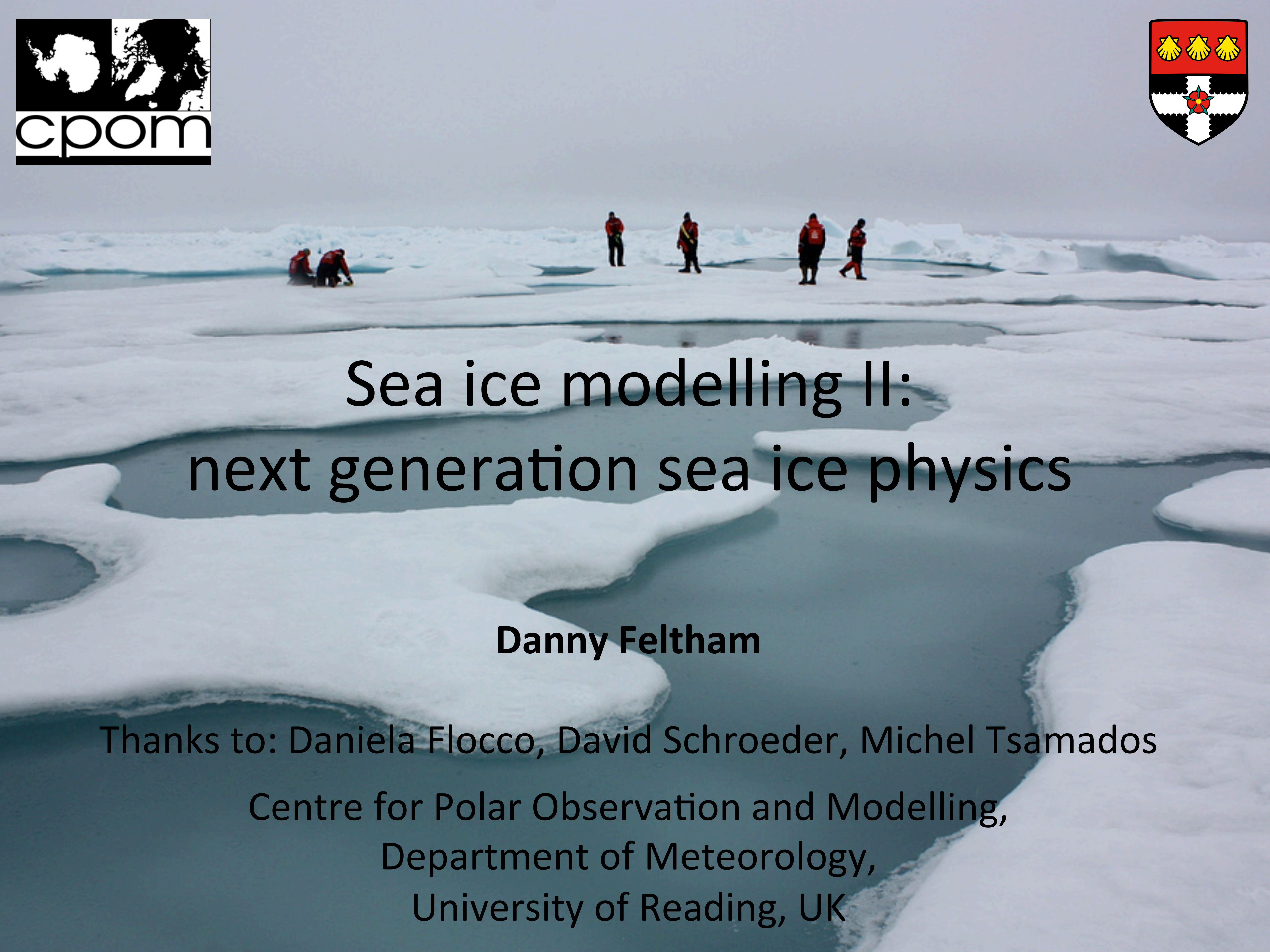


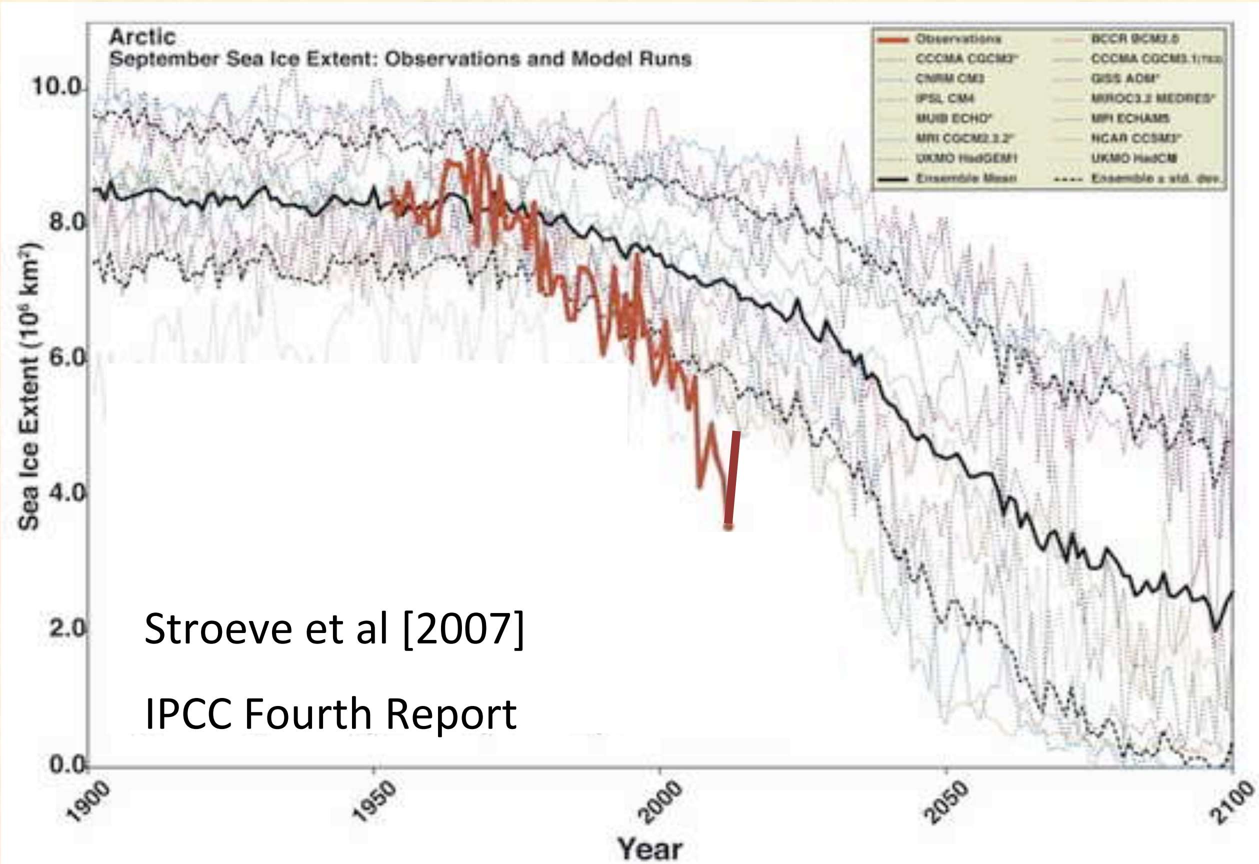
Sea ice modelling II: next generation sea ice physics

Danny Feltham

Thanks to: Daniela Flocco, David Schroeder, Michel Tsamados

Centre for Polar Observation and Modelling,
Department of Meteorology,
University of Reading, UK

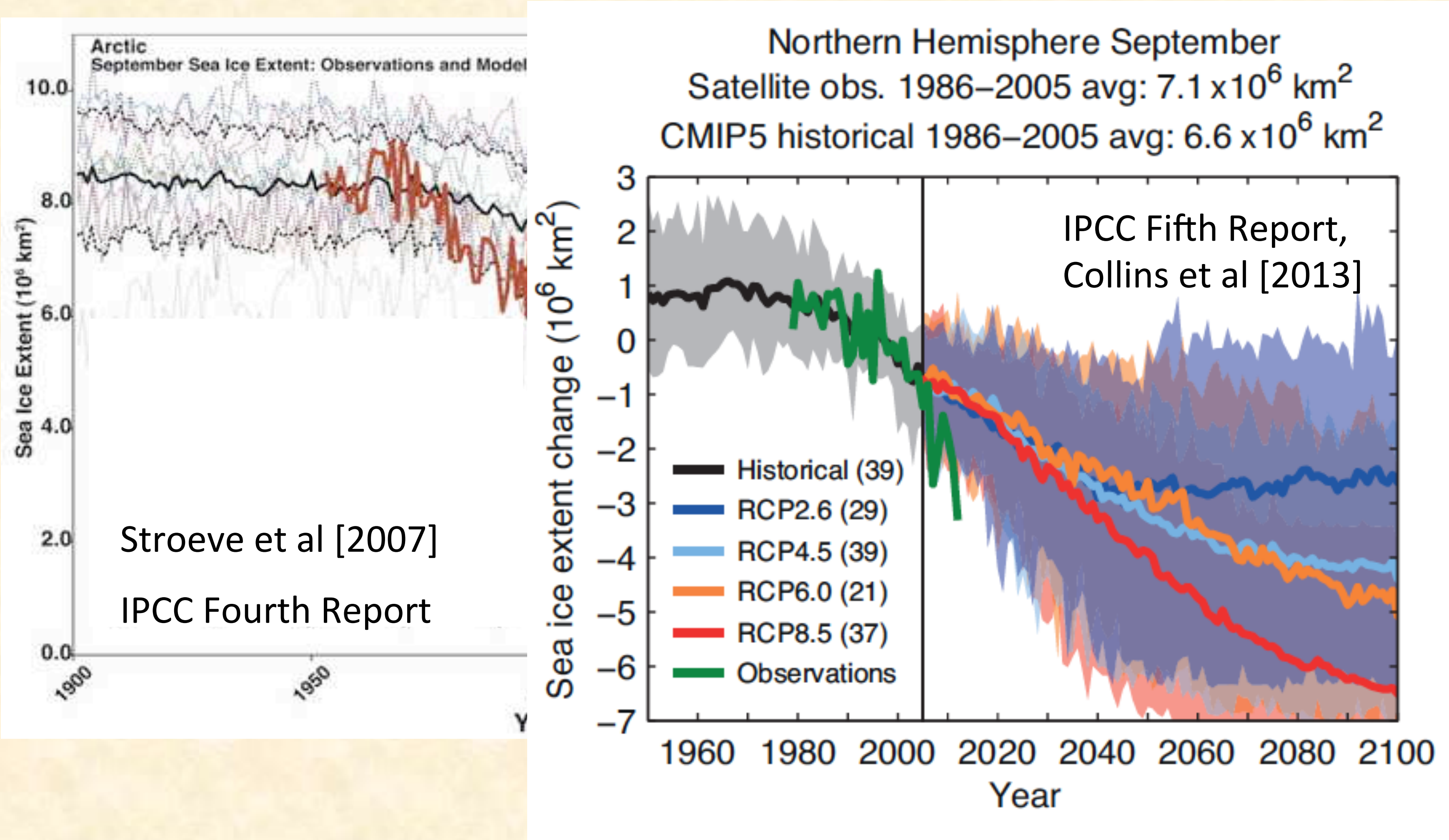
Rapid reduction of summer Arctic sea ice extent



Disparity between climate prediction of sea ice and reality can be due to many factors (natural variability, inaccurate simulation of atmosphere, ocean, etc.).

But, uncertainty in existing sea ice physics is *sufficient* to account for the disparity.

Rapid reduction of summer Arctic sea ice extent



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But, uncertainty in existing sea ice physics is *sufficient* to account for the disparity.

Modelling sea ice in climate models

Sea ice models are formulated as **continuum** expressions of **local balances of momentum, mass, and heat,** which are mediated through various **processes**. In practise, sea ice processes are divided into:

- **Dynamic** processes, which control the motion of ice cover, deformation, and redistribution of thickness. Example processes are air and ocean drag, ridging, sliding, and rupture (rheology).
- **Thermodynamic** processes, which 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 (extent, concentration, volume) of sea ice is determined by an **intimate mixture** of dynamic and thermodynamic processes.

A sea ice lead, formed in divergence, results in rapid new ice growth.

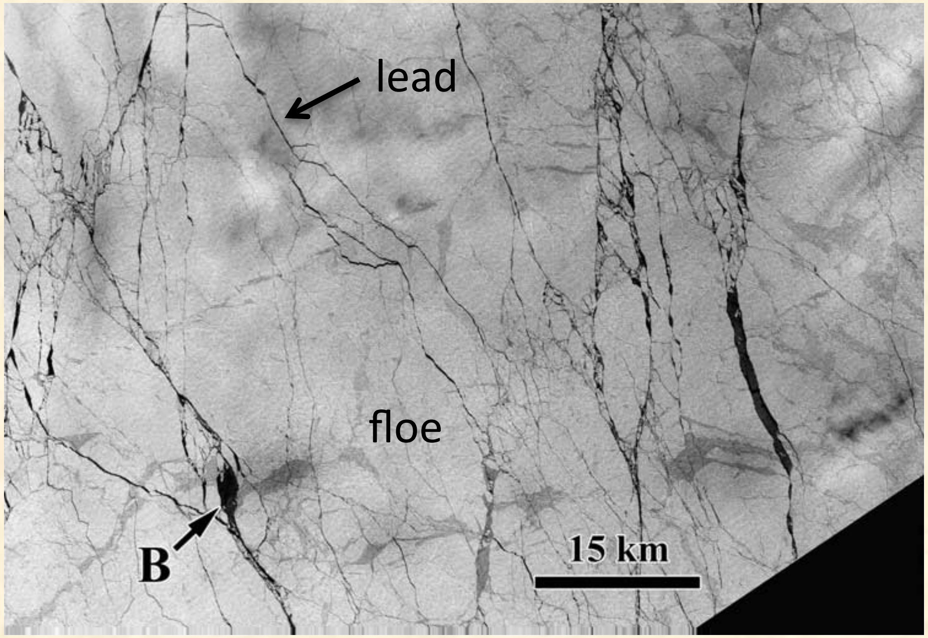
Talk structure

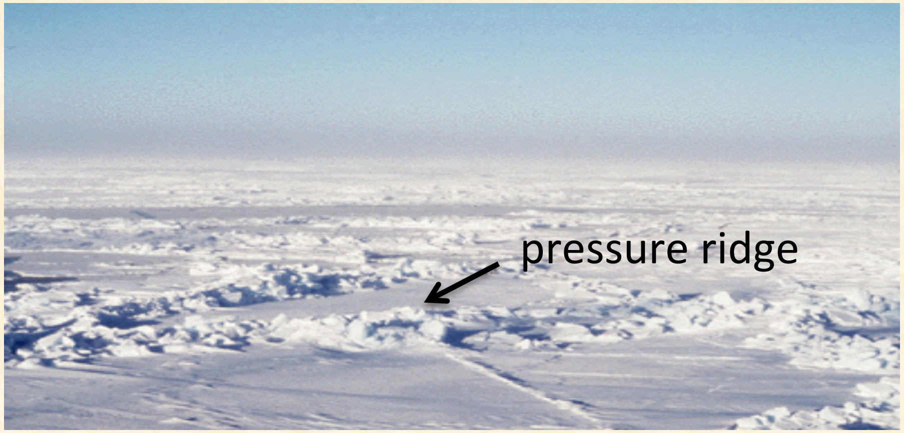
1. Introduction to sea ice (brief)

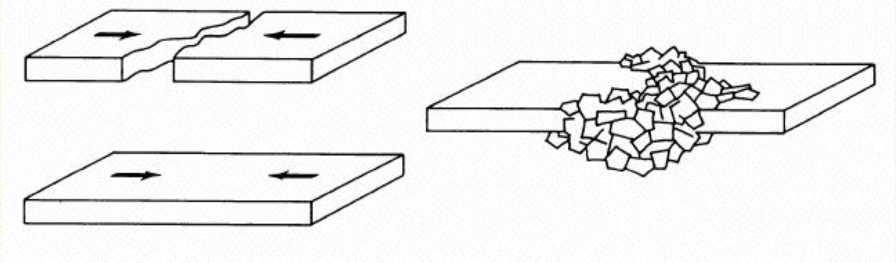
2. Form drag
3. Anisotropic sea ice rheology
4. Melt ponds

5. Summary remarks

Sea ice floes, leads, and ridges



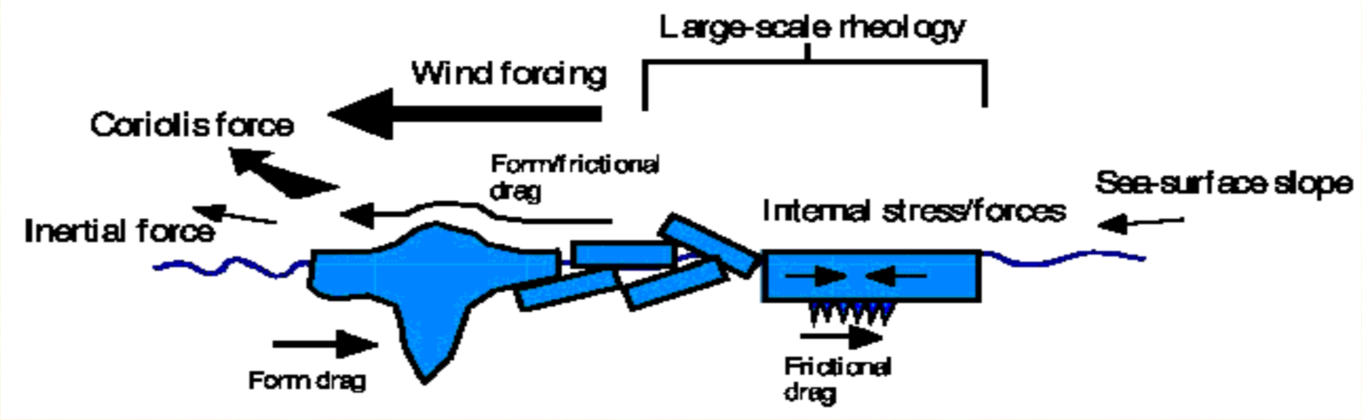




The sea ice cover consists of **floes** that are 0.1-10 km wide and 0.1-5 m thick; they are separated by cracks or **leads**. The floes may be frozen together to form **floe aggregates** or be separate. Ice area concentration typically 0.90-0.99.

Pressure ridges form when floes collide with, and over ride, each other. The ice sheet breaks up into blocks that are pushed into **sails** and **keels**. Pressure ridges can be many kilometres in length; the sails and keels are approximately triangular.

Horizontal momentum balance of sea ice

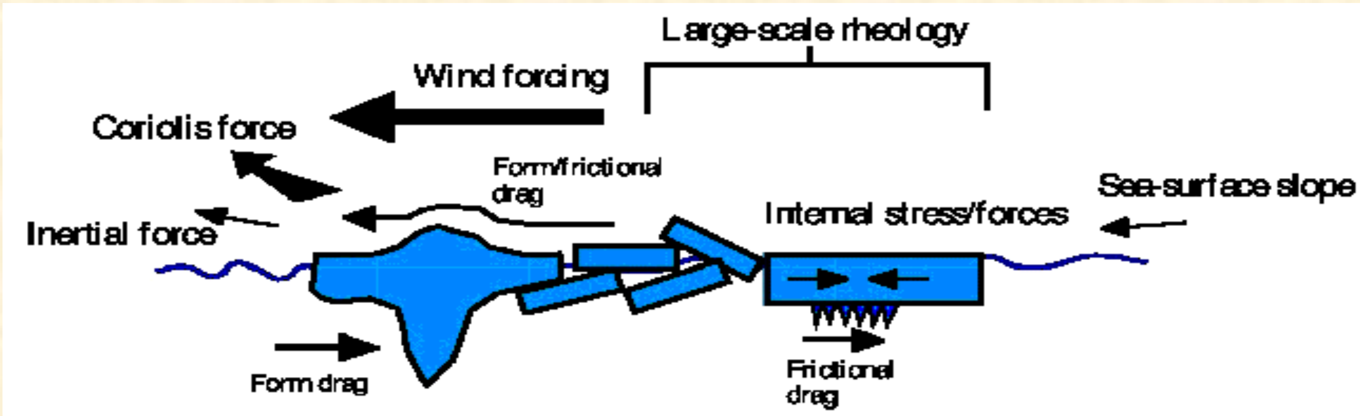


Vertically-integrated (i.e. horizontal) momentum balance is:

$$m\frac{D\mathbf{u}}{Dt} = \boldsymbol{\tau}_{\mathrm{a}} + \boldsymbol{\tau}_{\mathrm{w}} + \nabla\cdot\boldsymbol{\sigma} - mf_C\mathbf{k}\times\mathbf{u} - mg\nabla H$$

mass X acceleration = air drag + ocean drag + ice-ice force + Coriolis "force" + gravity force from sea surface tilt

Horizontal momentum balance of sea ice



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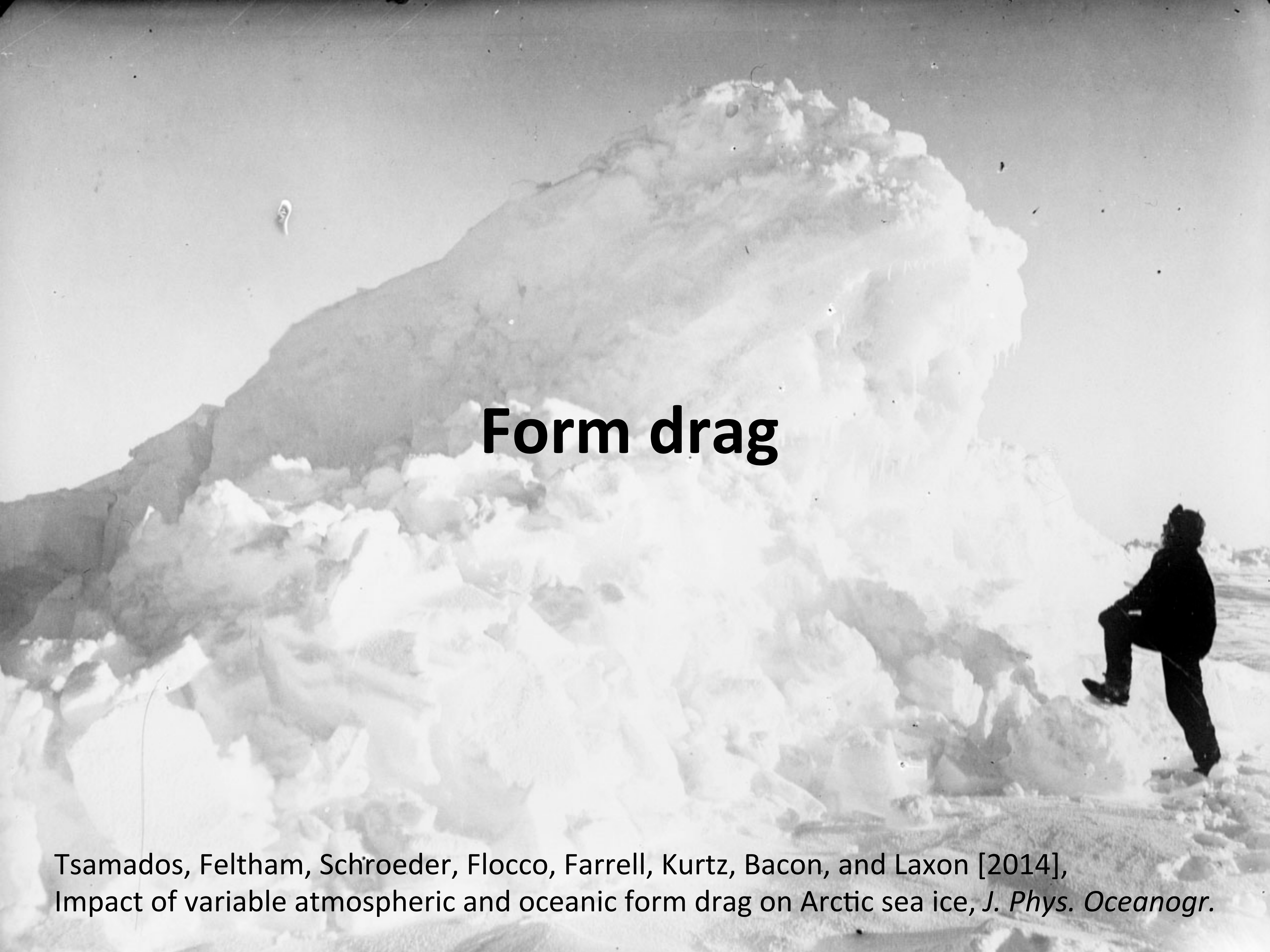


Form drag

Tsamados, Feltham, Schroeder, Flocco, Farrell, Kurtz, Bacon, and Laxon [2014], Impact of variable atmospheric and oceanic form drag on Arctic sea ice, *J. Phys. Oceanogr.*

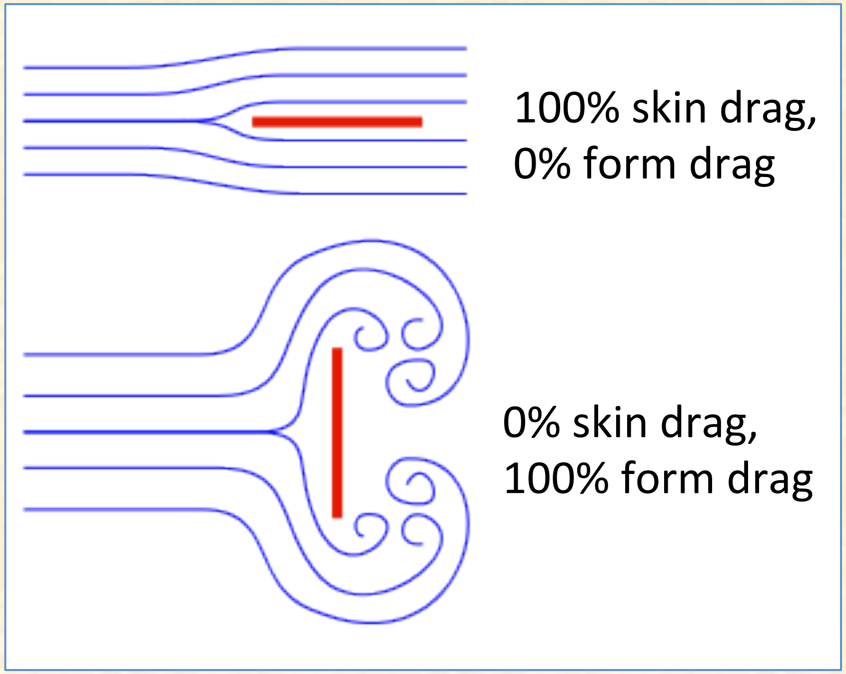
Form drag

- Scaling analysis of Navier-Stokes equations demonstrates that drag laws must be of the form

$$\tau = \rho C_D U^2$$

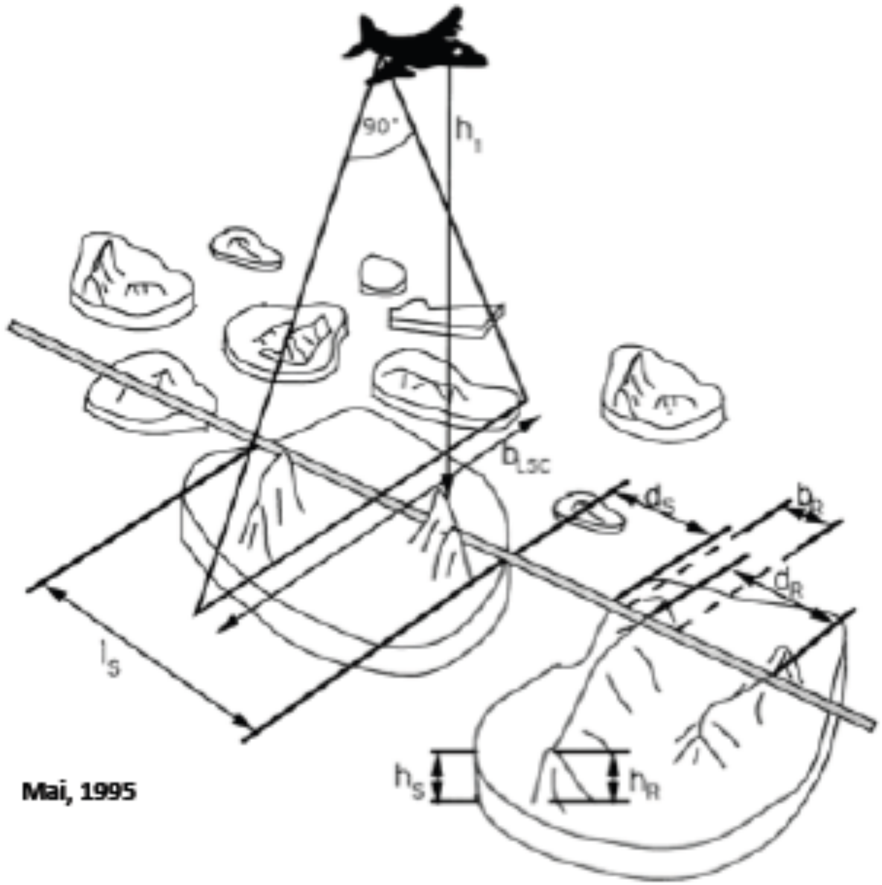
where C_D is a function of Reynolds number (weak dependence typically ignored) and geometry of surface/obstacle.

- This drag law accounts for both **skin drag** and **form drag** by suitable choice of C_D.

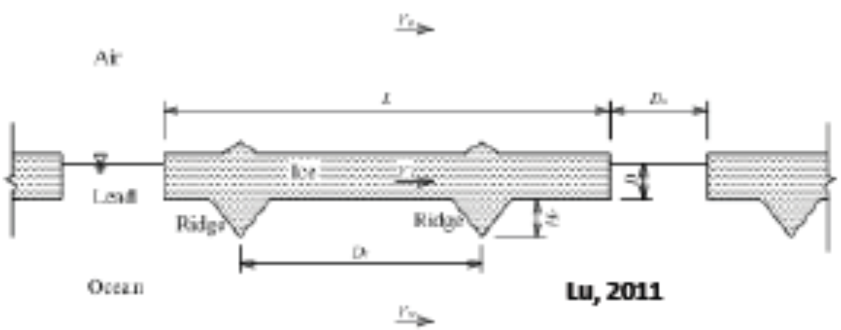


- Topography of the ice cover creates spatially and temporally variable **form drag**, which is ignored in current models that treat the air and ice drag coefficients as **constants**.
- Form drag from a regular array of obstacles of height *H* with spacing *D* takes the form $C_D = c\dfrac{H}{D}S^2$ where *c* is geometry dependent (measured), and *S* is a "sheltering" function accounting for the obstacle's wake
- Atmospheric boundary layer (in)stability is separately accounted for models using Monin-Obukhov theory.

Topography needed to calculate form drag



Mai, 1995



Lu, 2011

Important parameters of the model (in parenthesis notation of schematics) :

- L : floe size (ls)
- A : ice concentration

Atmosphere :

- Hf : freeboard (hs)
- Hr : ridge height (hr)
- Dr : distance between ridges (dr)
- Df : distance between floes (ds)
- Lp : pond size (not shown)
- Hp : elevation of ice surface relative to pond surface (not shown)

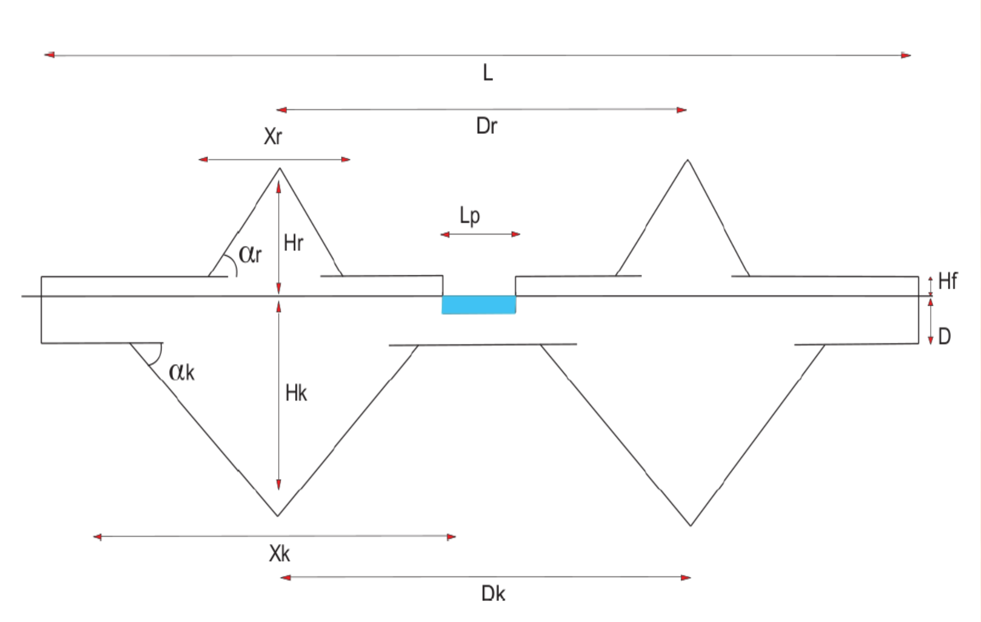
Ocean

- Hd : floe draft (D)
- Hk : ridge keel height (Hr)
- Dk : distance between keels (Dr)

Topography parameters in sea ice model

- Sea ice model CICE (Hunke, 2013) gives deformed ice volume and area. Using observations of ridge/keel shape (Martin, 2007) allows us to extract ridge/keel spacing and size.

- Freeboard and draft come from hydrostasy (accounting for snow and melt ponds).



- Floe size and spacing are related to ice concentration using empirical formulas (Lupkes et al 2012; Lupkes and Birnbaum, 2005)

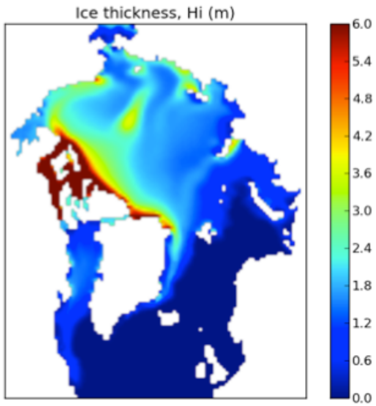
$$L = L_{min}\left(\frac{A_\star}{A_\star - A}\right)^{\beta}, \qquad D_f = L\left(1-\sqrt{A}\right)/\sqrt{A}.$$

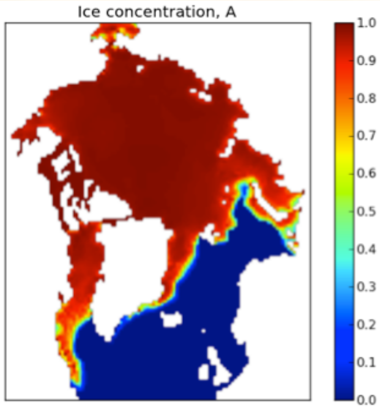
- Melt pond size comes from empirical formula (Fetter and Untersteiner, 1998) and CICE pond area (Flocco et al, 2012)

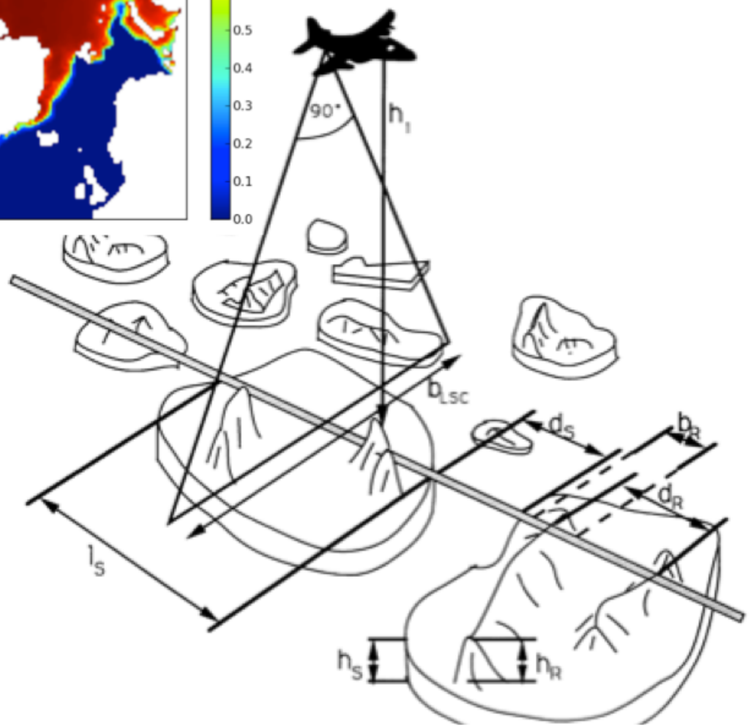
$$L_p = L_{pmin}A_p + L_{pmax}(1-A_p)$$

Parameters introduced into the sea ice model CICE

Concentration and thickness are standard in sea ice models







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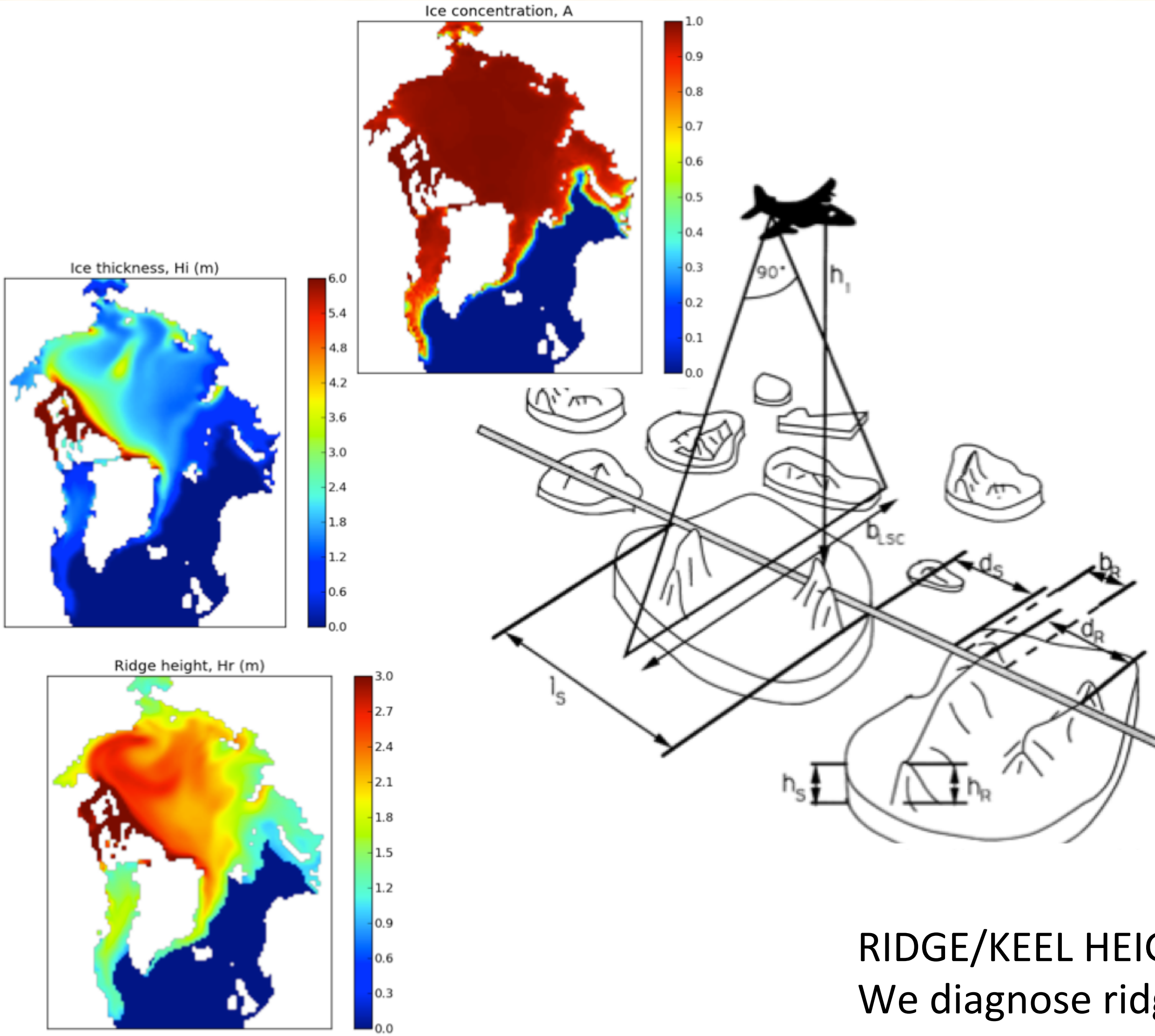
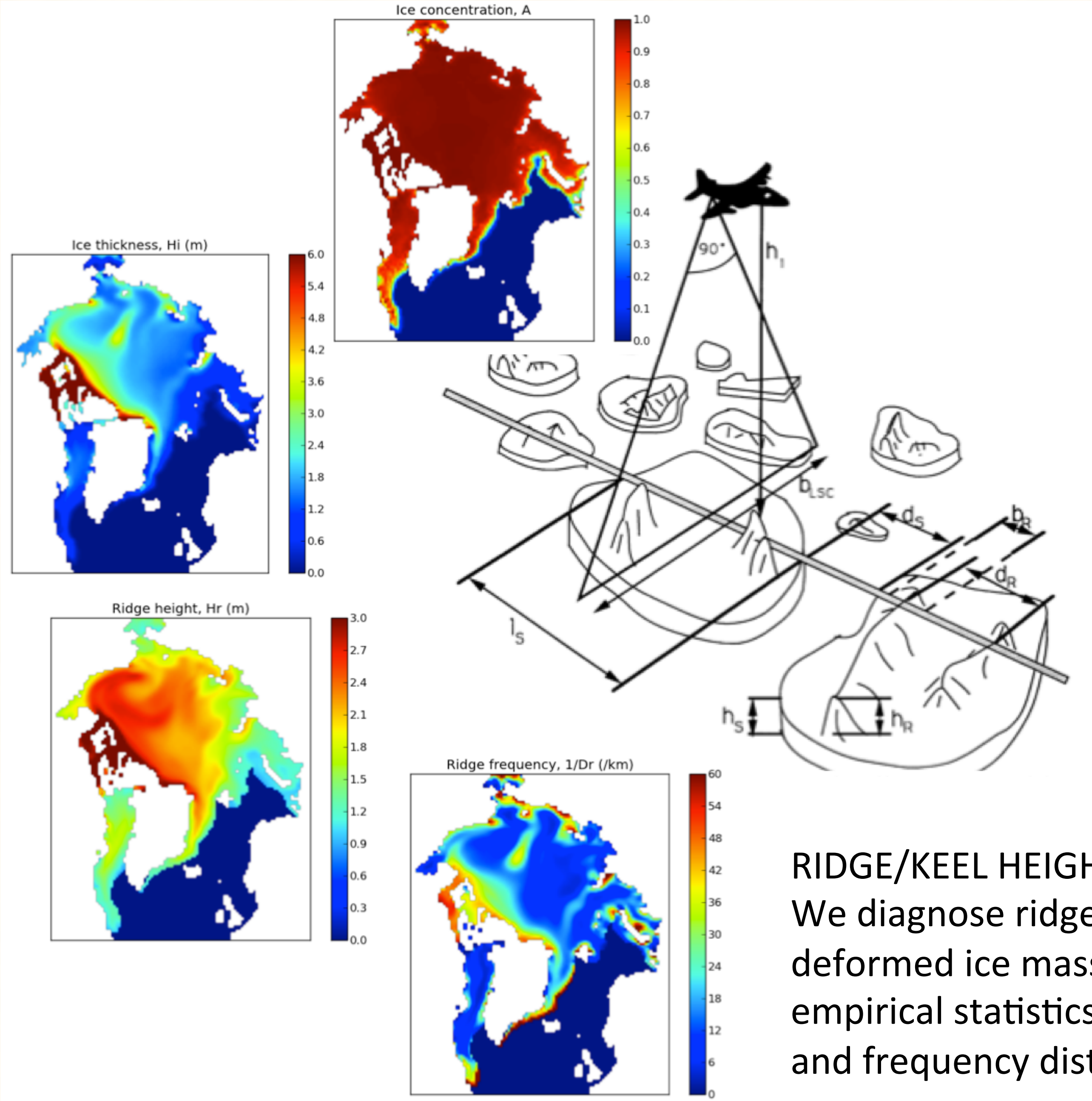


RIDGE/KEEL HEIGHT AND SPACING

We diagnose ridge properties from a deformed ice mass balance and empirical statistics on ridge/keel height and frequency distributions

Parameters introduced into the sea ice model CICE



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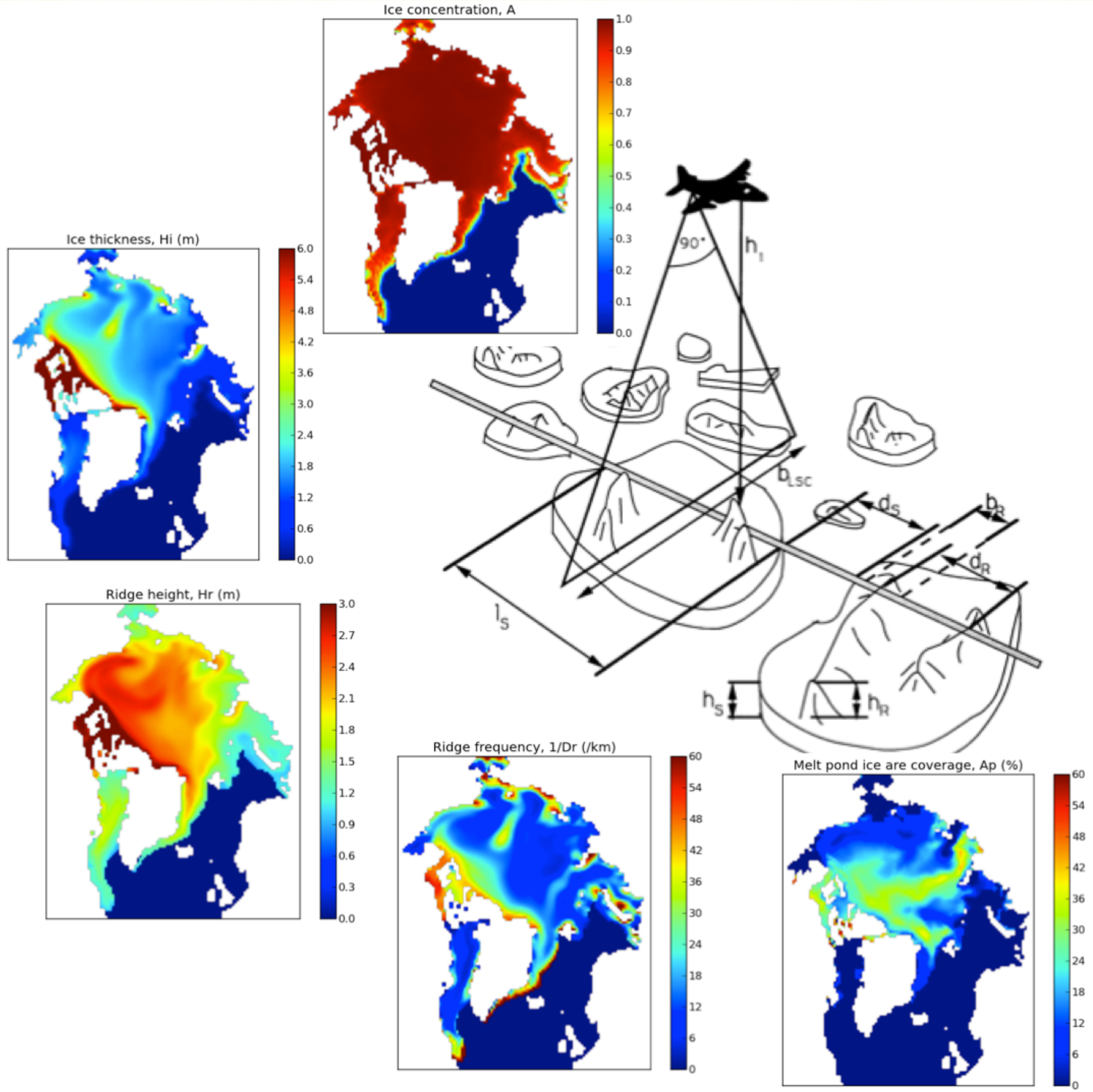
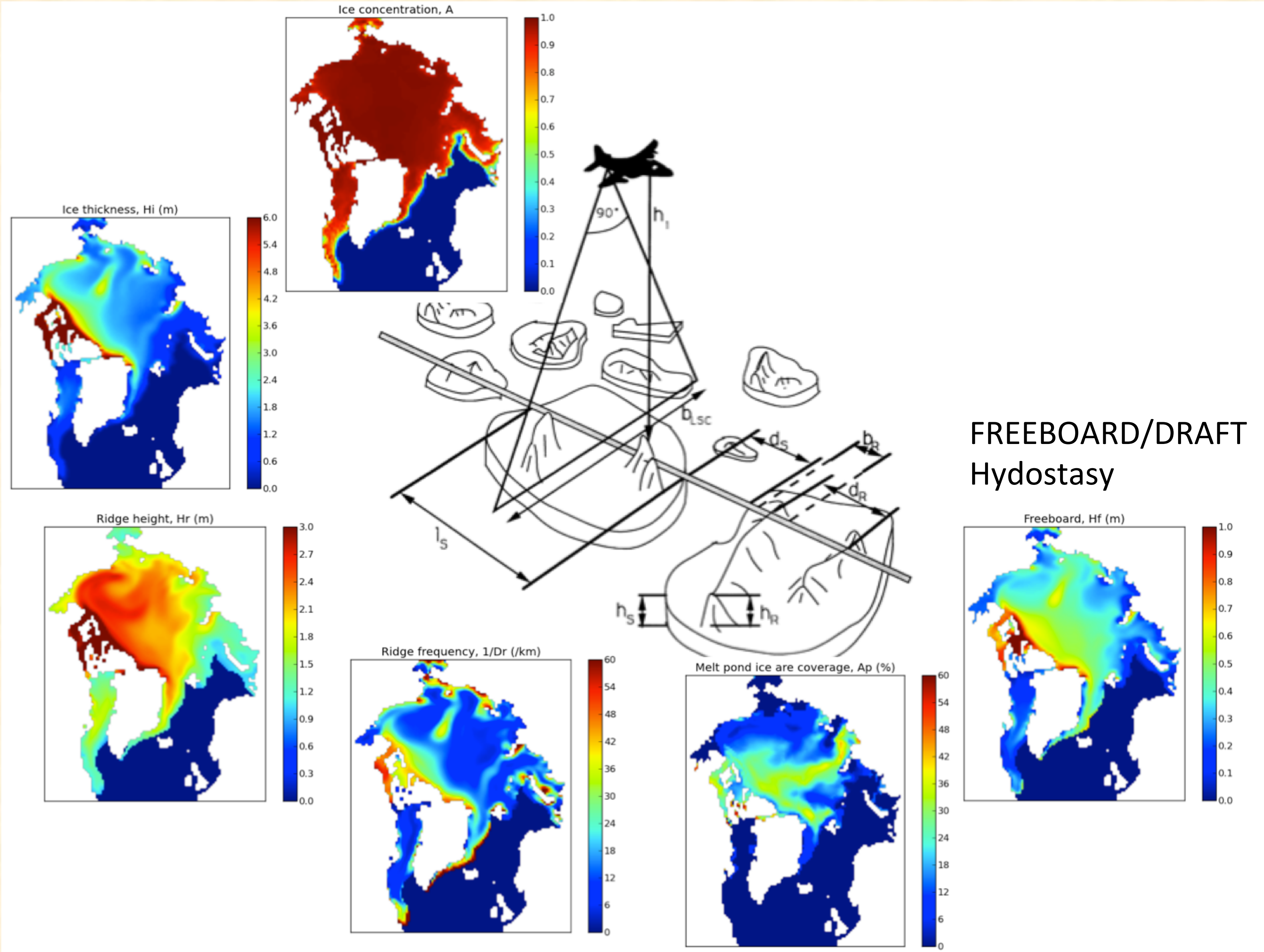


POND AREA
We developed a melt pond theory e.g. Flocco et al [2010;2012], soon to be included in climate models

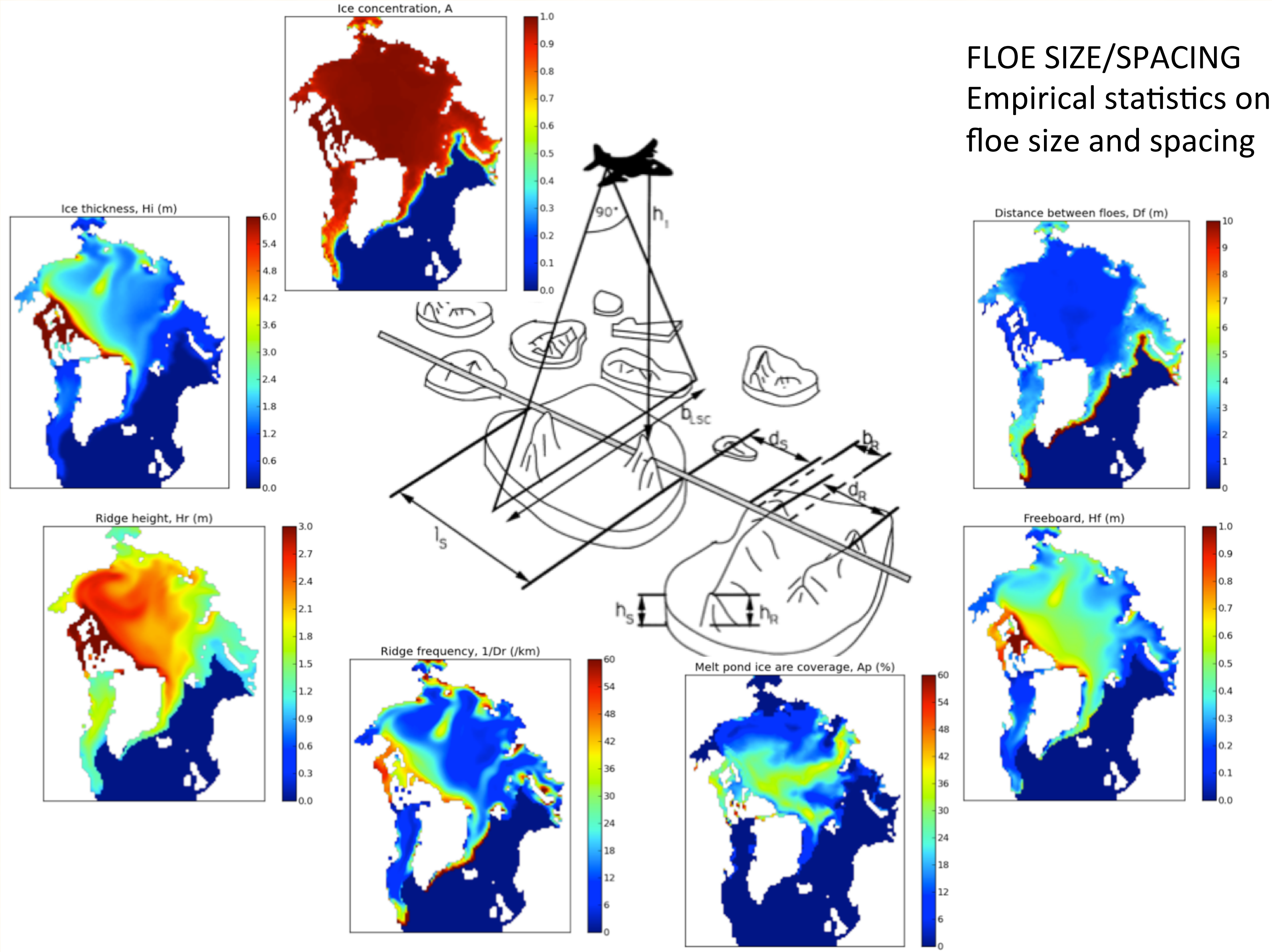
Parameters introduced into the sea ice model CICE



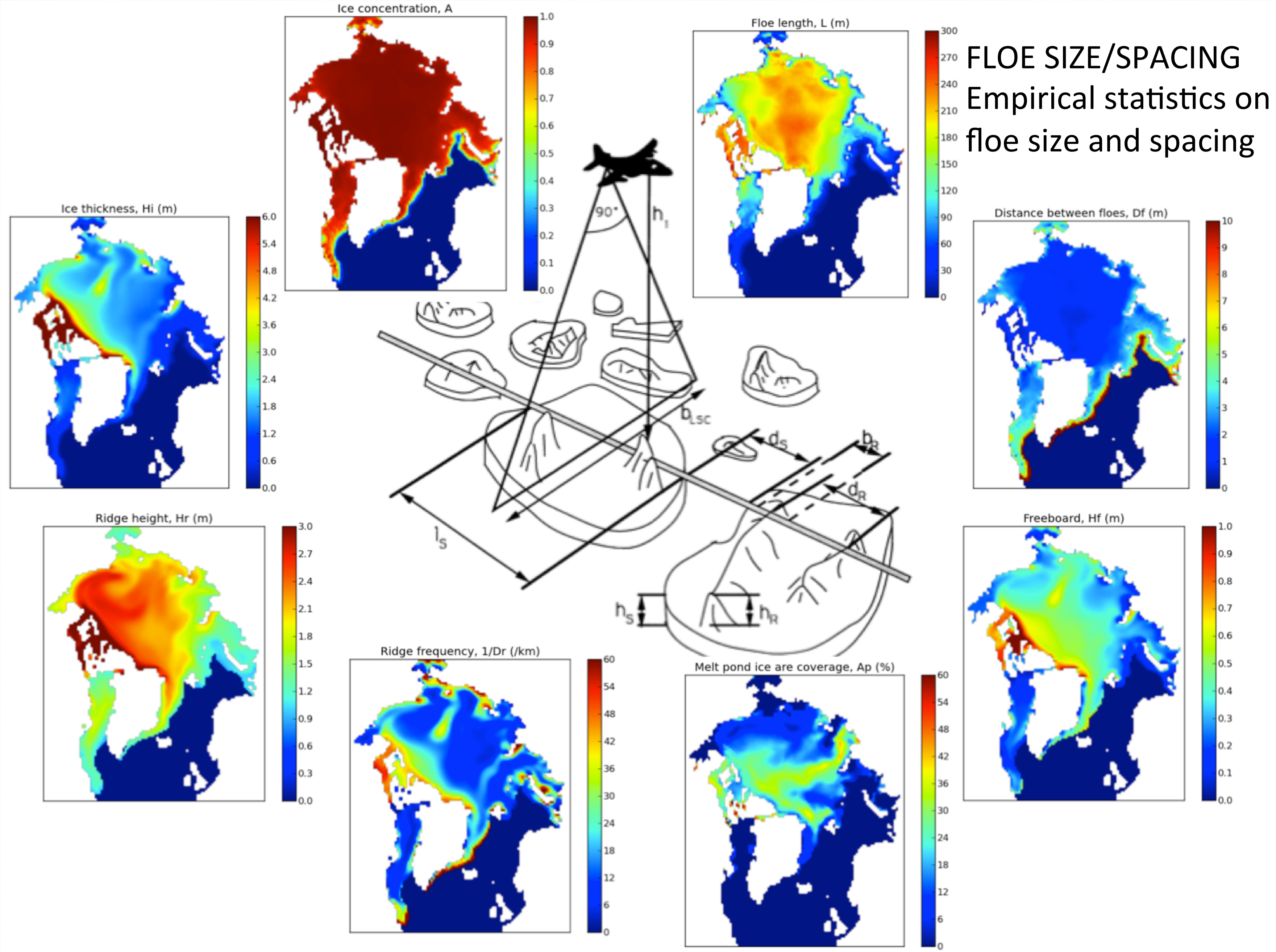
FREEBOARD/DRAFT
Hydostasy

Parameters introduced into the sea ice model CICE

FLOE SIZE/SPACING
Empirical statistics on floe size and spacing



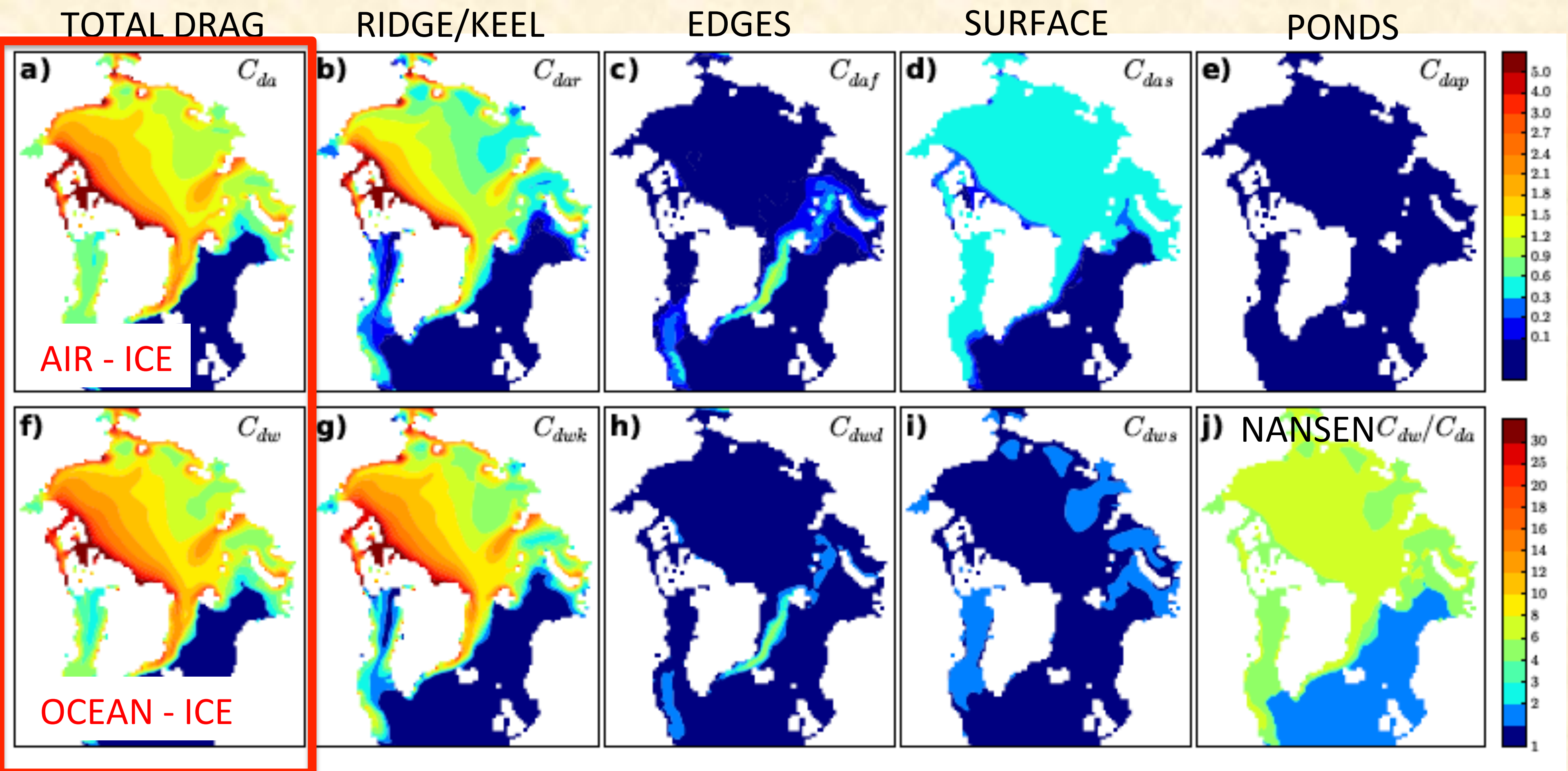
Parameters introduced into the sea ice model CICE



FLOE SIZE/SPACING
Empirical statistics on floe size and spacing

Map of drag coefficients, average March 1990-2007

CICE sea ice model run in forced mode, ERA forcing, 10 year spin up [Tsamados et al, 2014].



- Spatial variation of total drag coefficient of a factor of 4

Map of drag coefficients, average March 1990-2007

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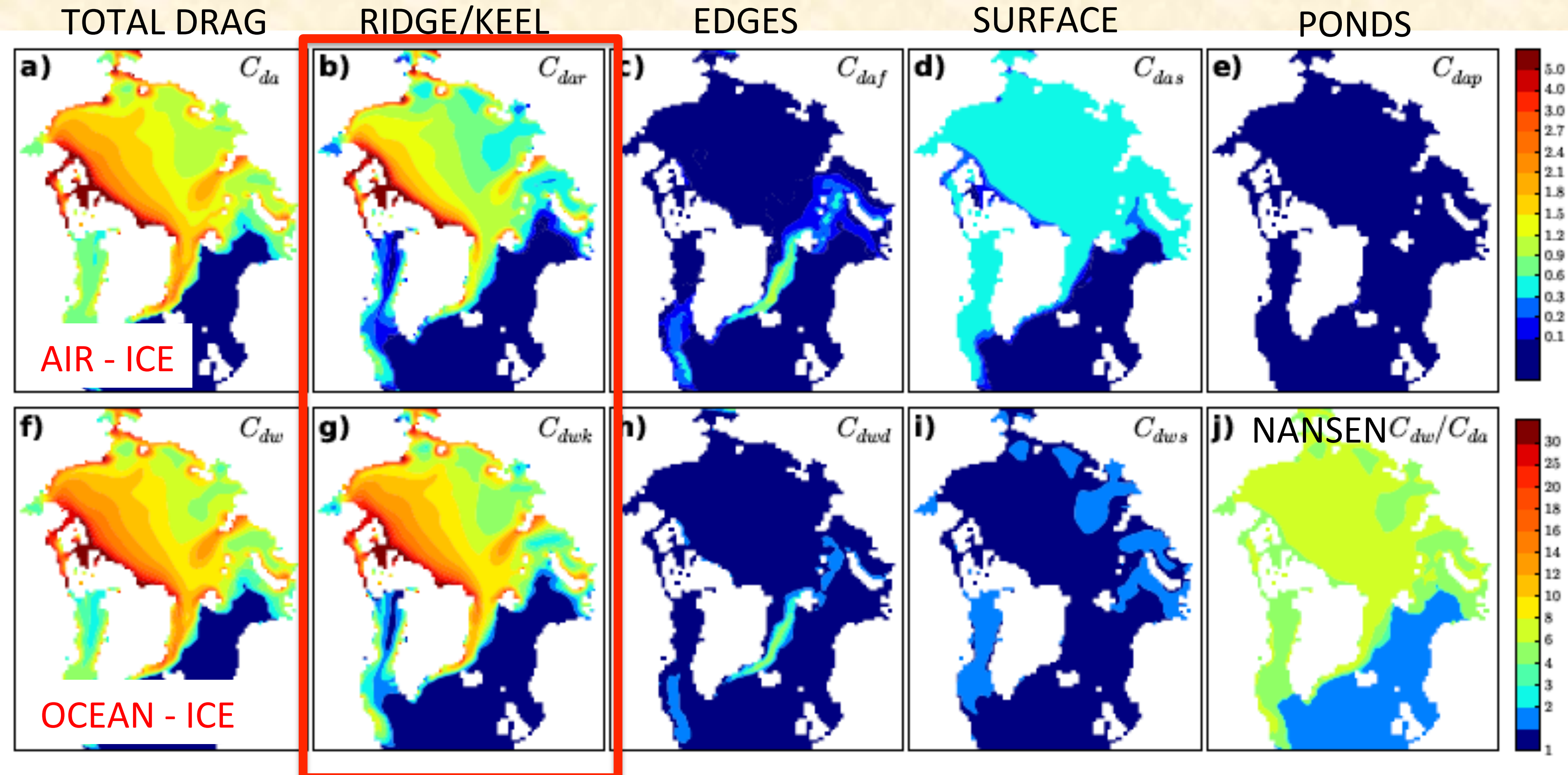

- Spatial variation of total drag coefficient of a factor of 4
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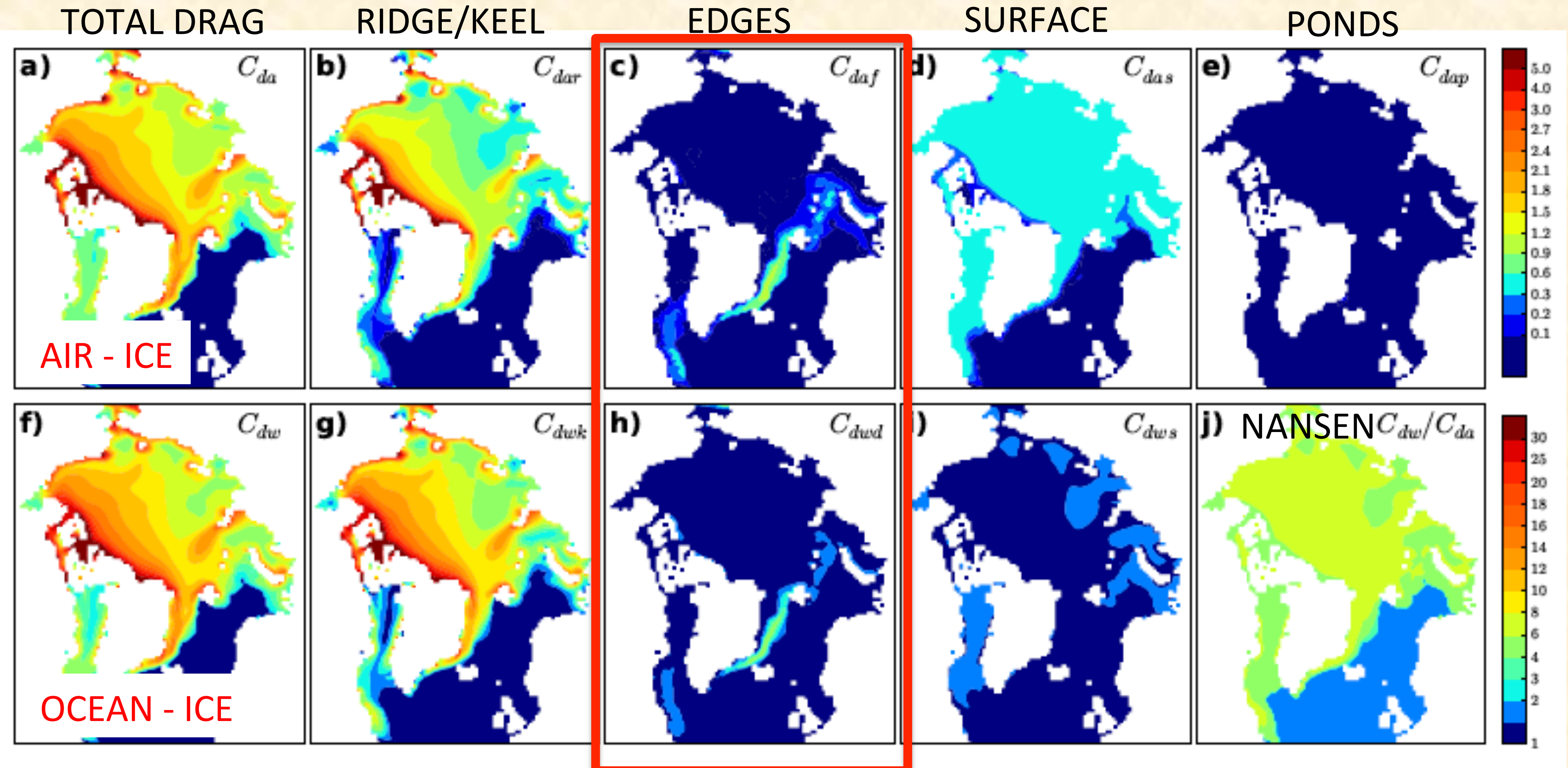
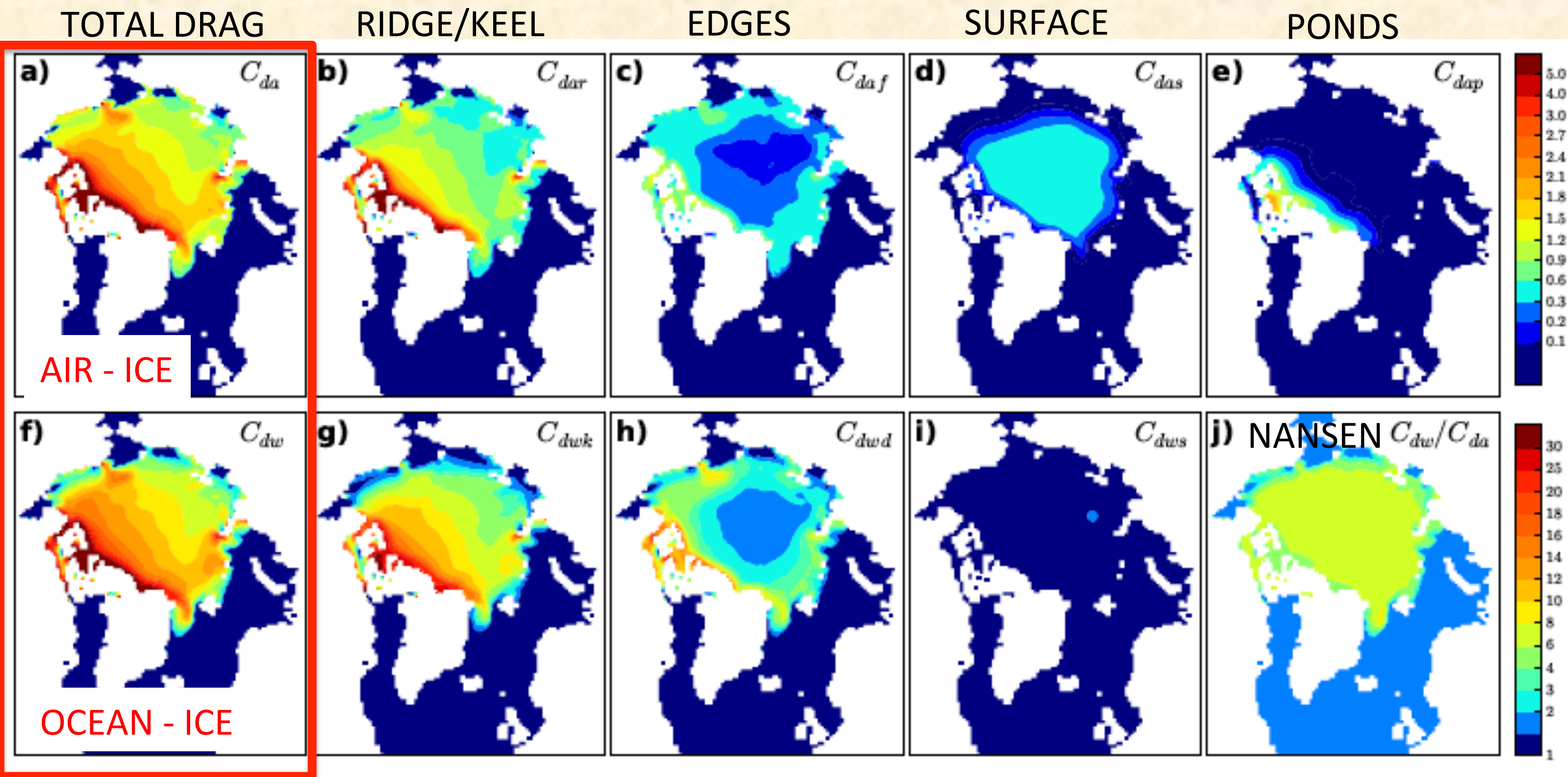


- Spatial variation of total drag coefficient of a factor of 4
- Ridge/keel form drag dominates
- Some floe edge drag in Marginal Ice Zone

Map of drag coefficients, average September 1990-2007



Tsamados et al, 2014

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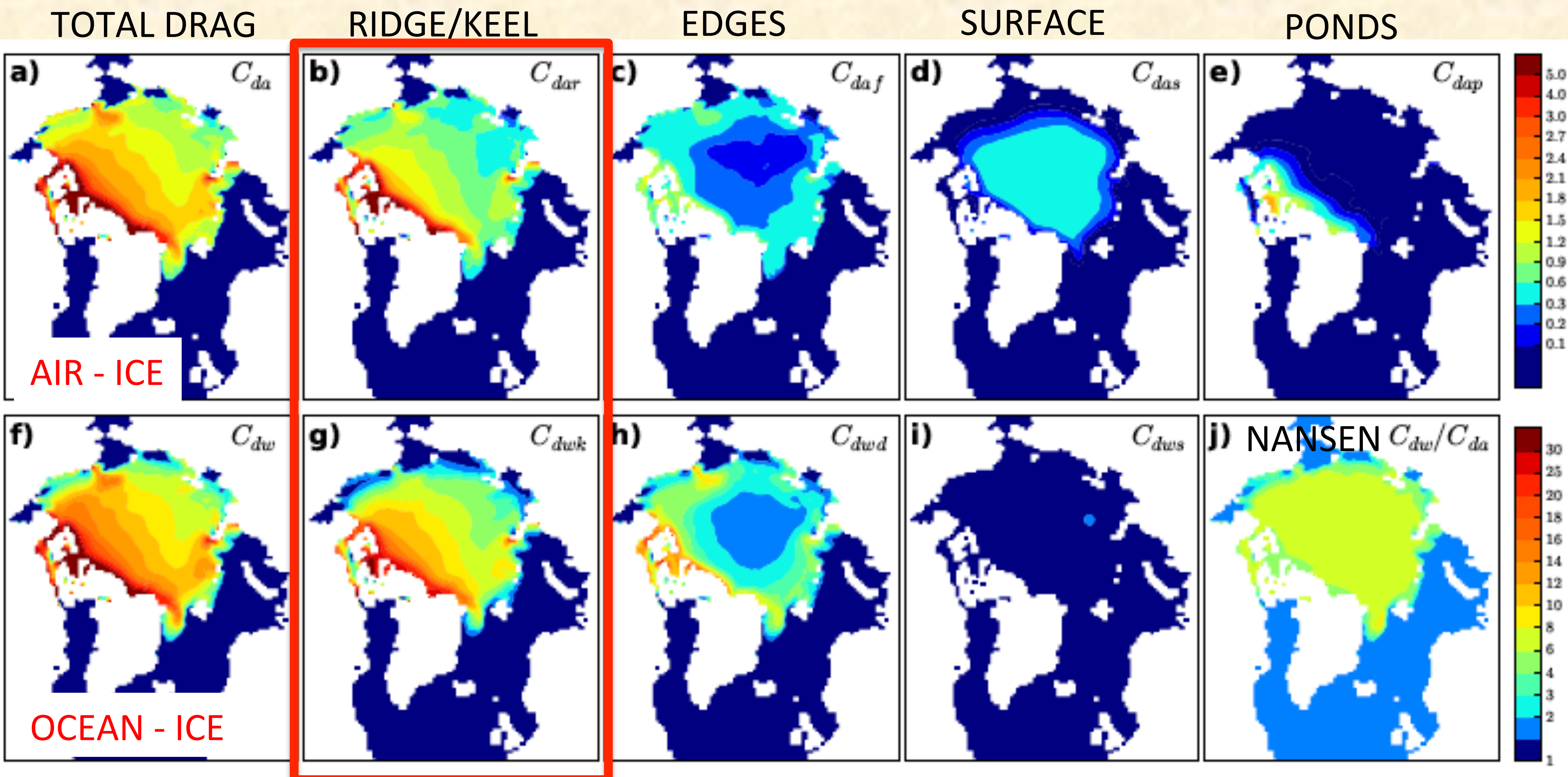

Tsamados et al, 2014

- Spatial variation of total drag coefficient of a factor of 4
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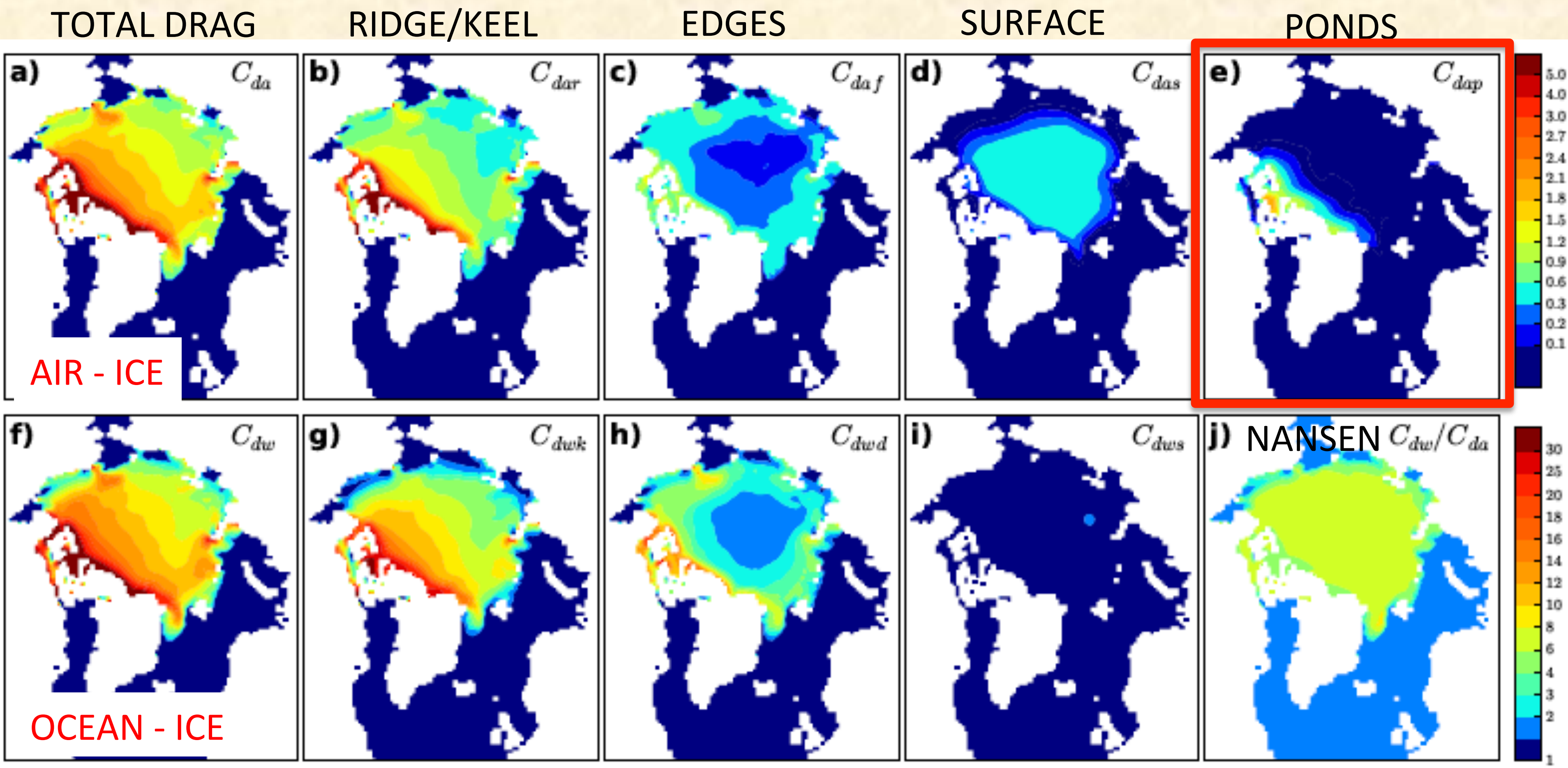
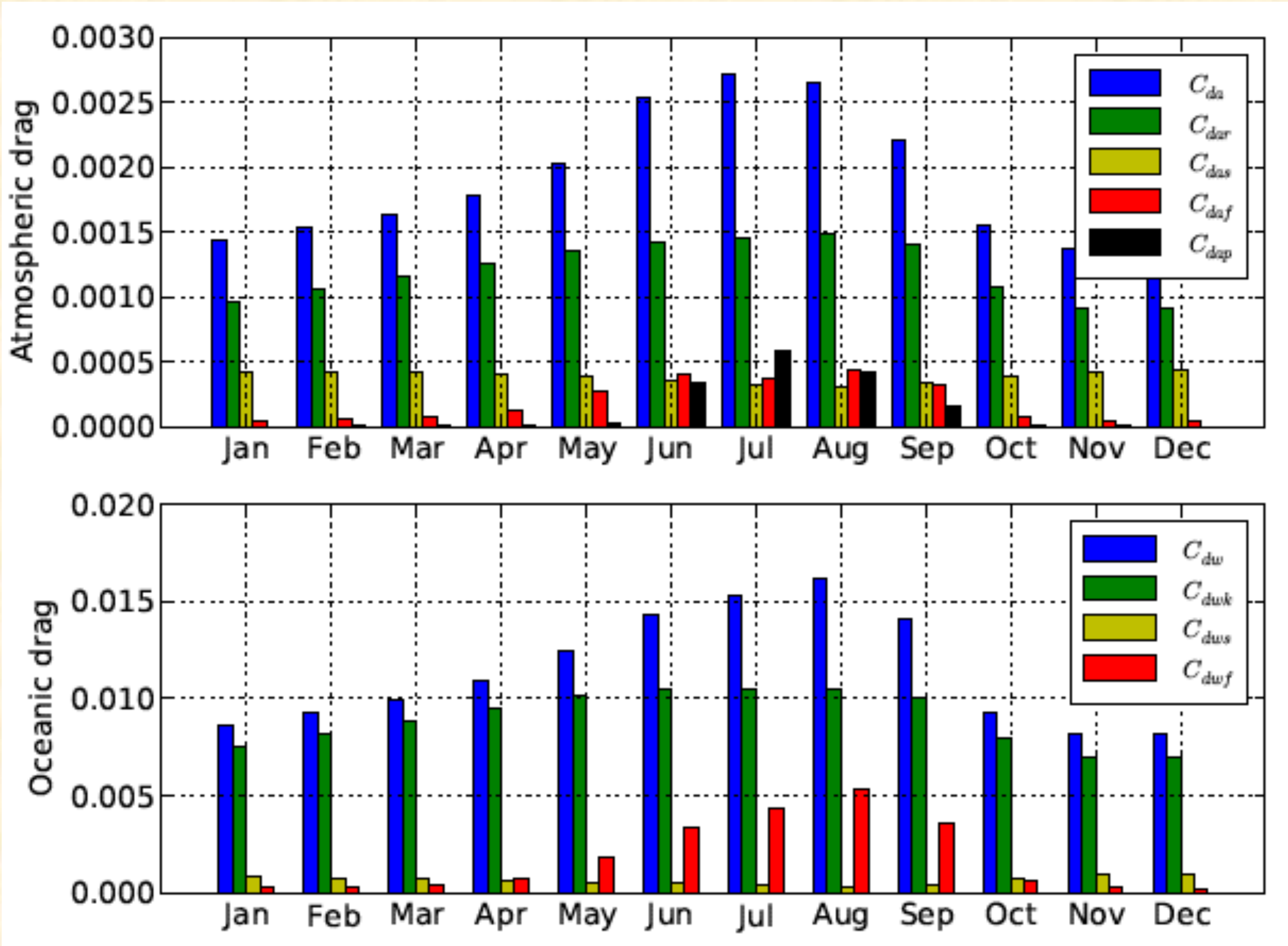


Tsamados et al, 2014

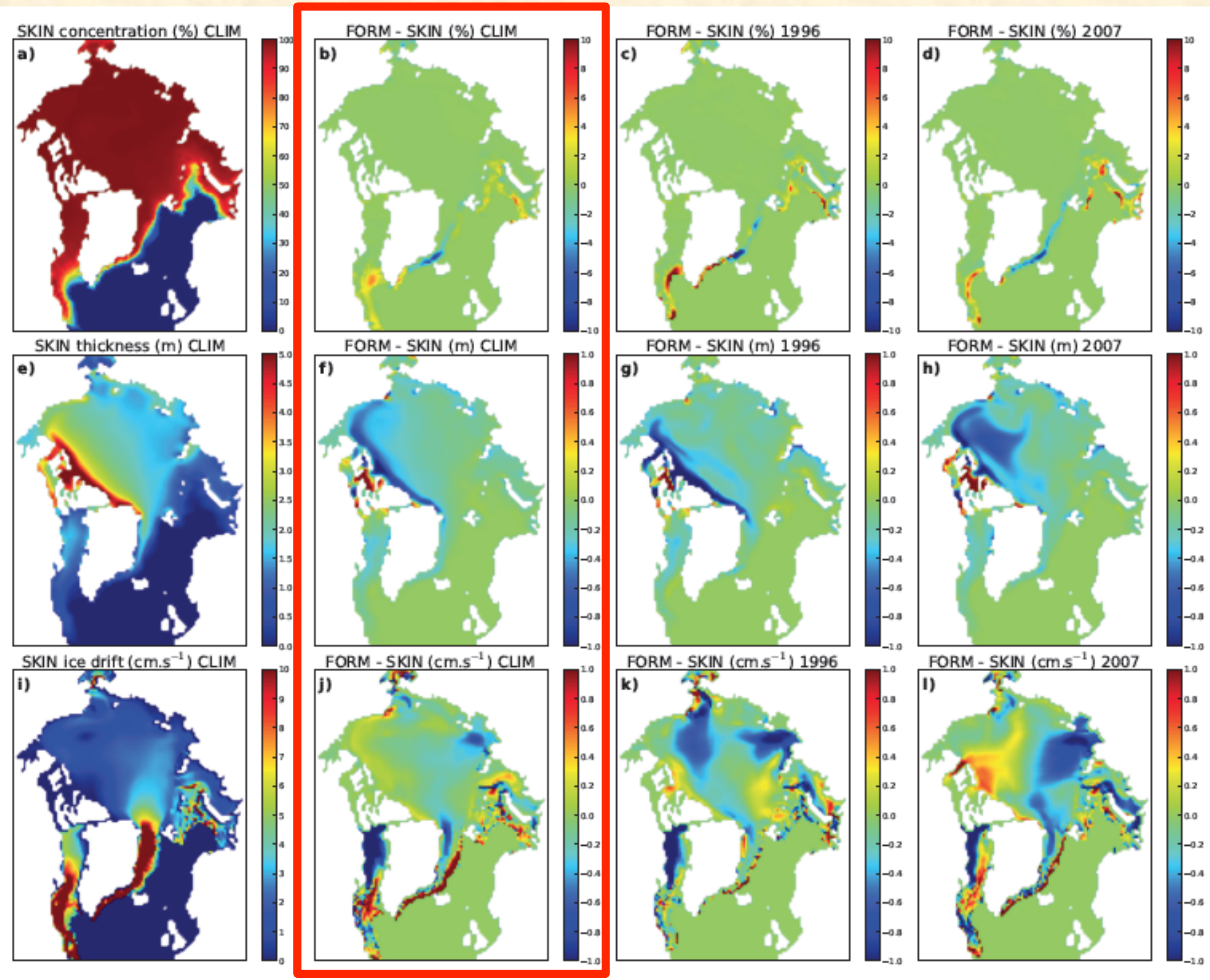
- Spatial variation of total drag coefficient of a factor of 4
- Ridges/keels form drag still dominates but floe edge drag becomes significant
- Pond edge drag small but comparable to skin drag over flat surfaces

Mean time dependence (1990-2007) of mean Arctic drag



- Seasonal variation of total drag coefficient by a factor of 2.

Impact of form drag on Arctic sea ice, March



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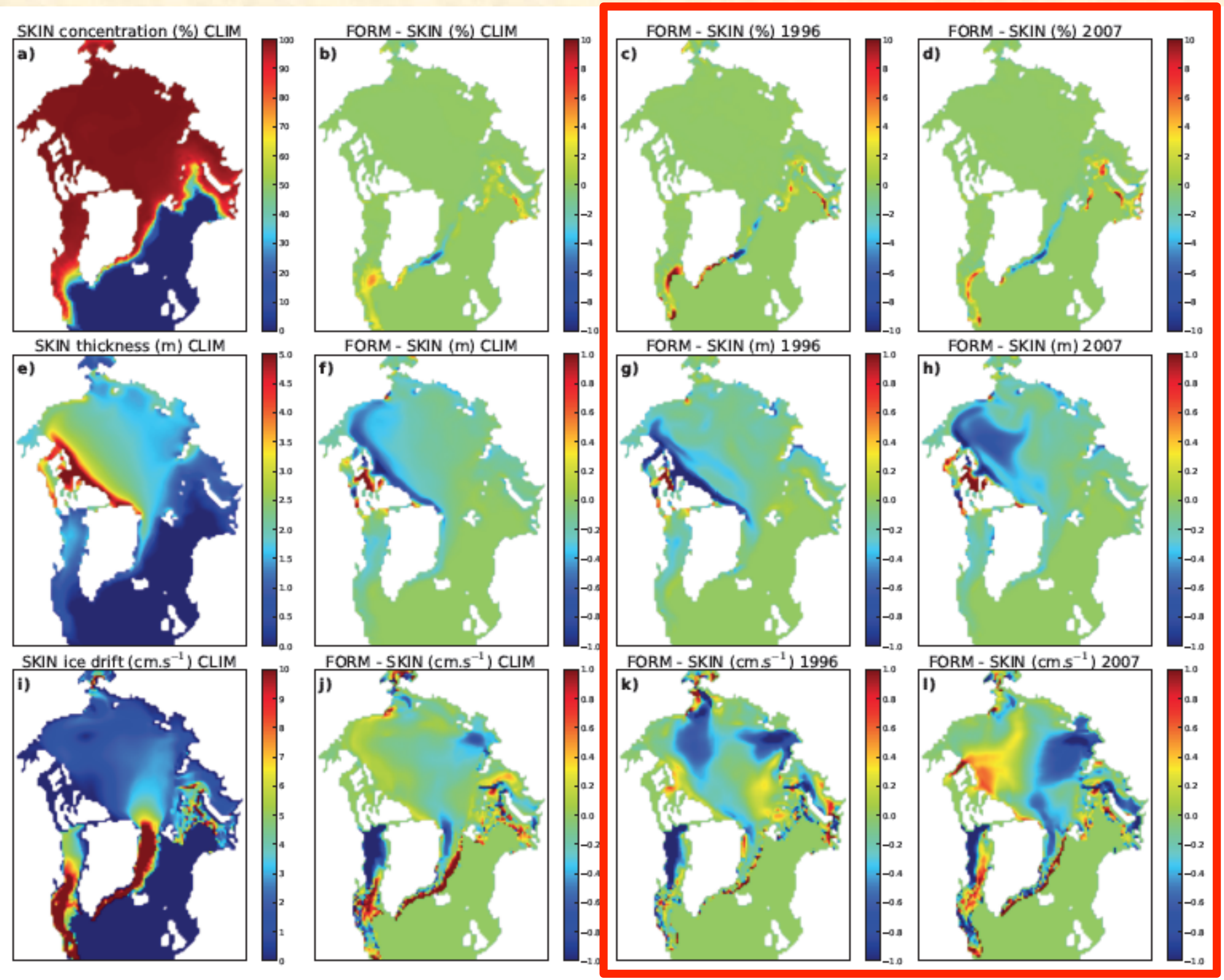
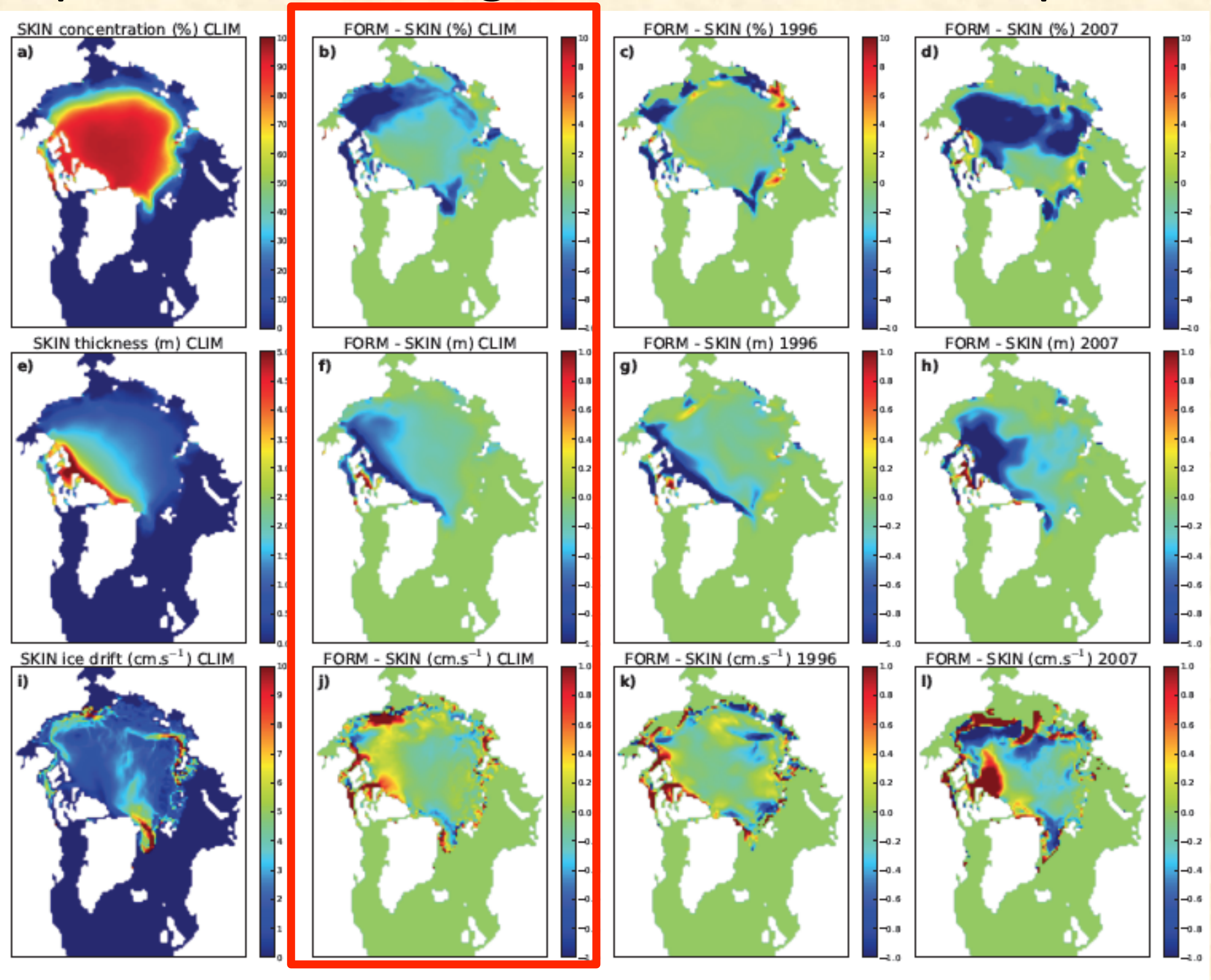


Impact of form drag on Arctic sea ice, September



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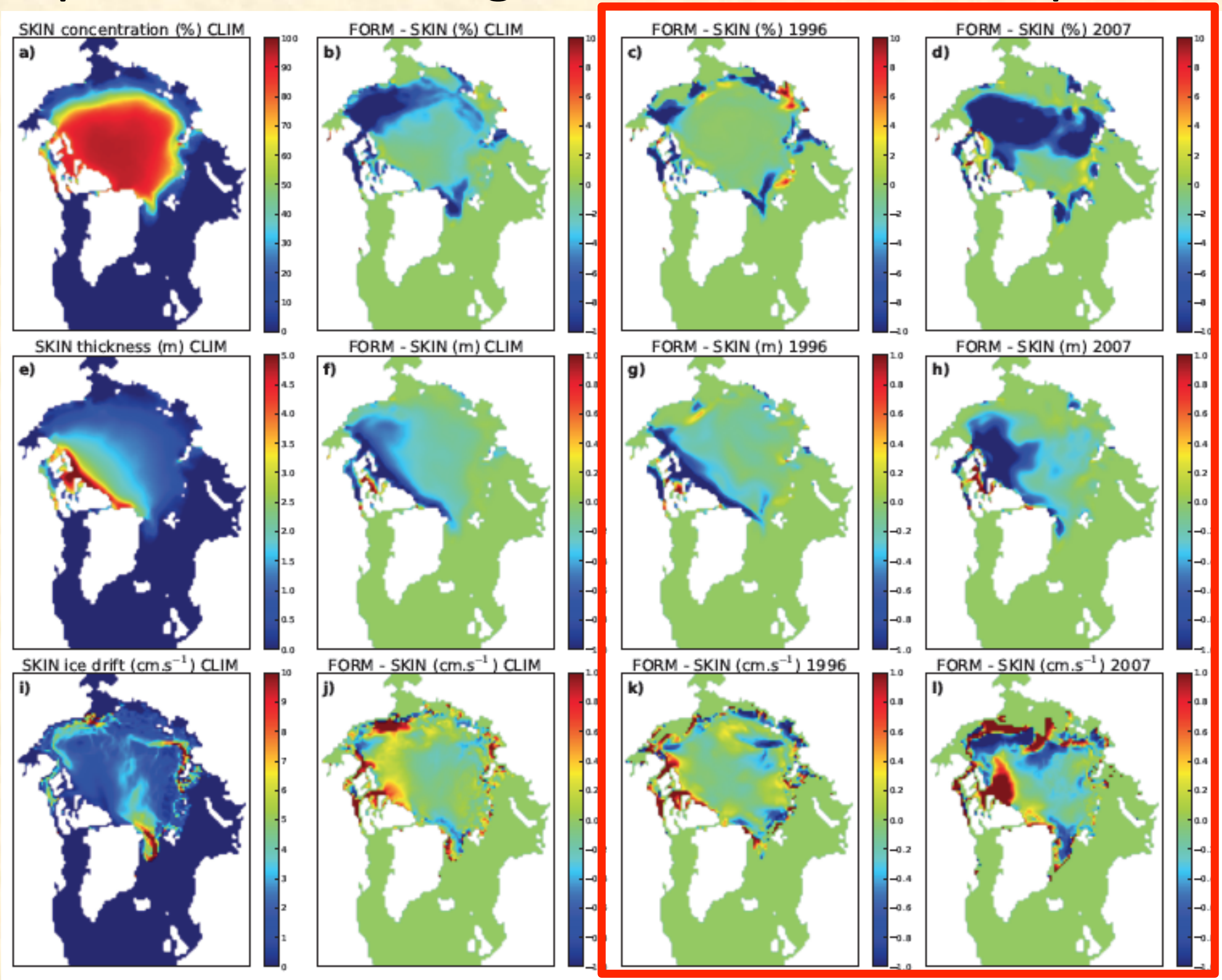
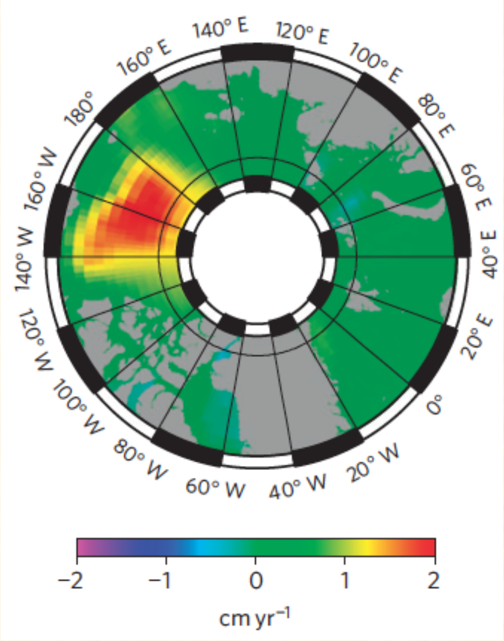


Summary remarks

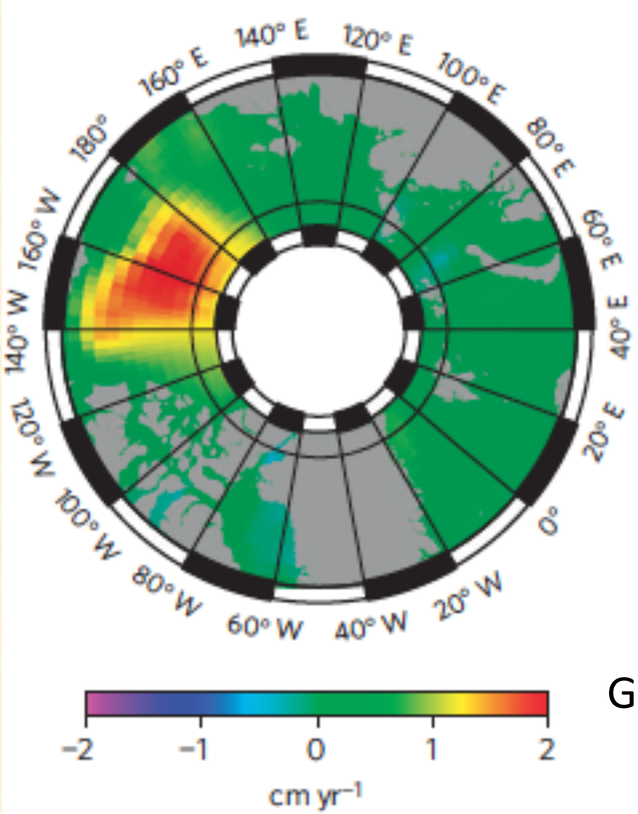
- **New parameterisation** of air-ice and ice-ocean drag developed and included into the CICE sea ice model that accounts for
    - Form drag from ridges/keels
    - Form drag from floe edges
    - Form drag from melt pond edges
    - Reduced skin drag due to sheltering

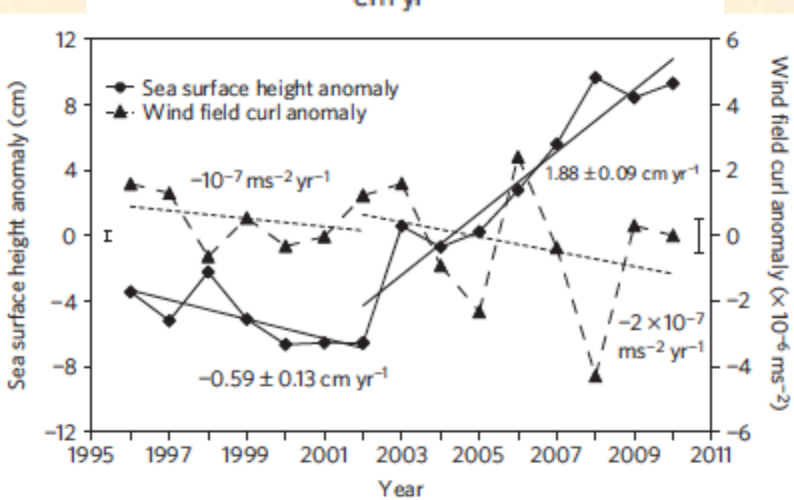
- Calibration of model parameters **ongoing**, in collaboration with the NASA **ICEBRIDGE** programme
- Impact of new drag physics on the ice state is **significant**, and introduces **additional spatial and temporal variability** into sea ice simulations
- We are currently working with NOC and the Met Office to explore the role of form drag in simulation of sea ice reduction and spin up of the Arctic Ocean



Giles et al, 2012

Spin up of Arctic Ocean





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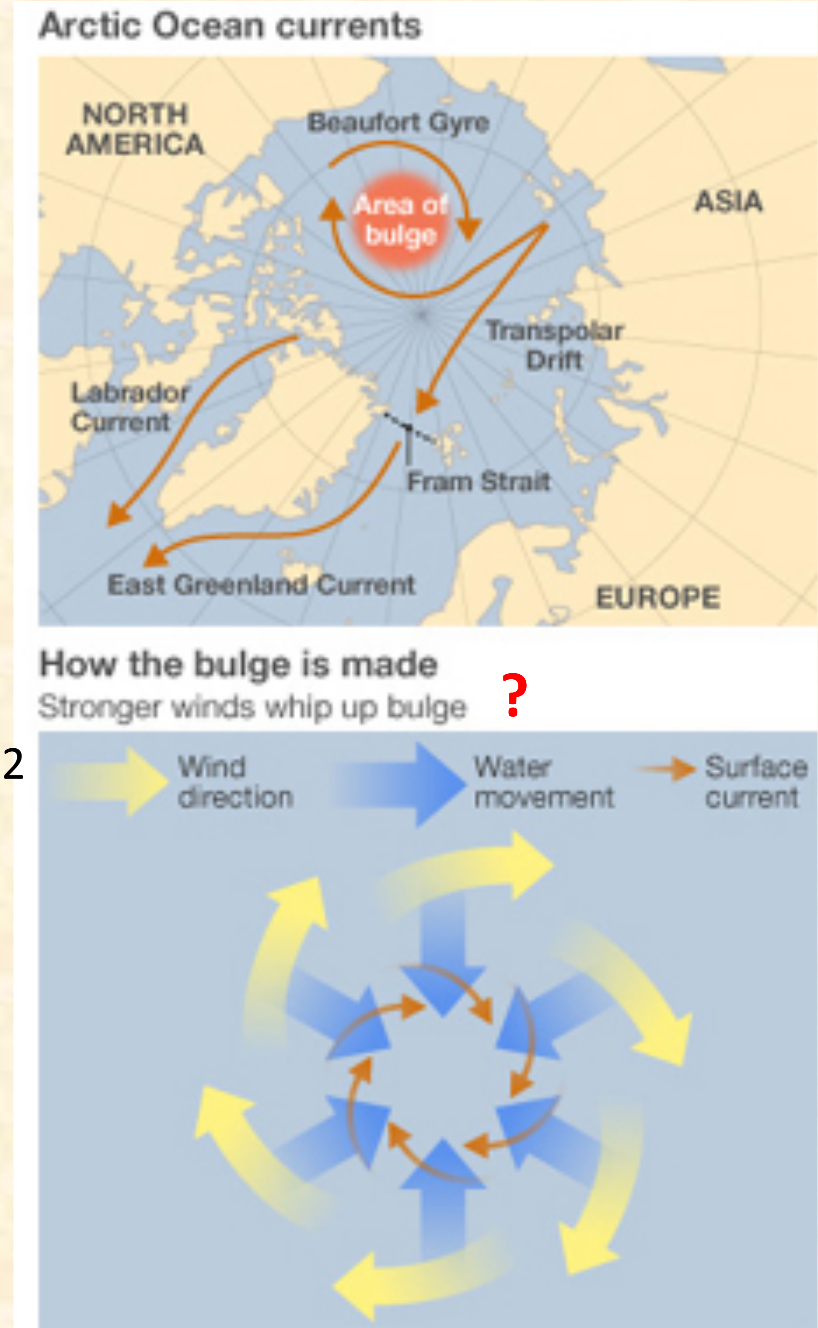
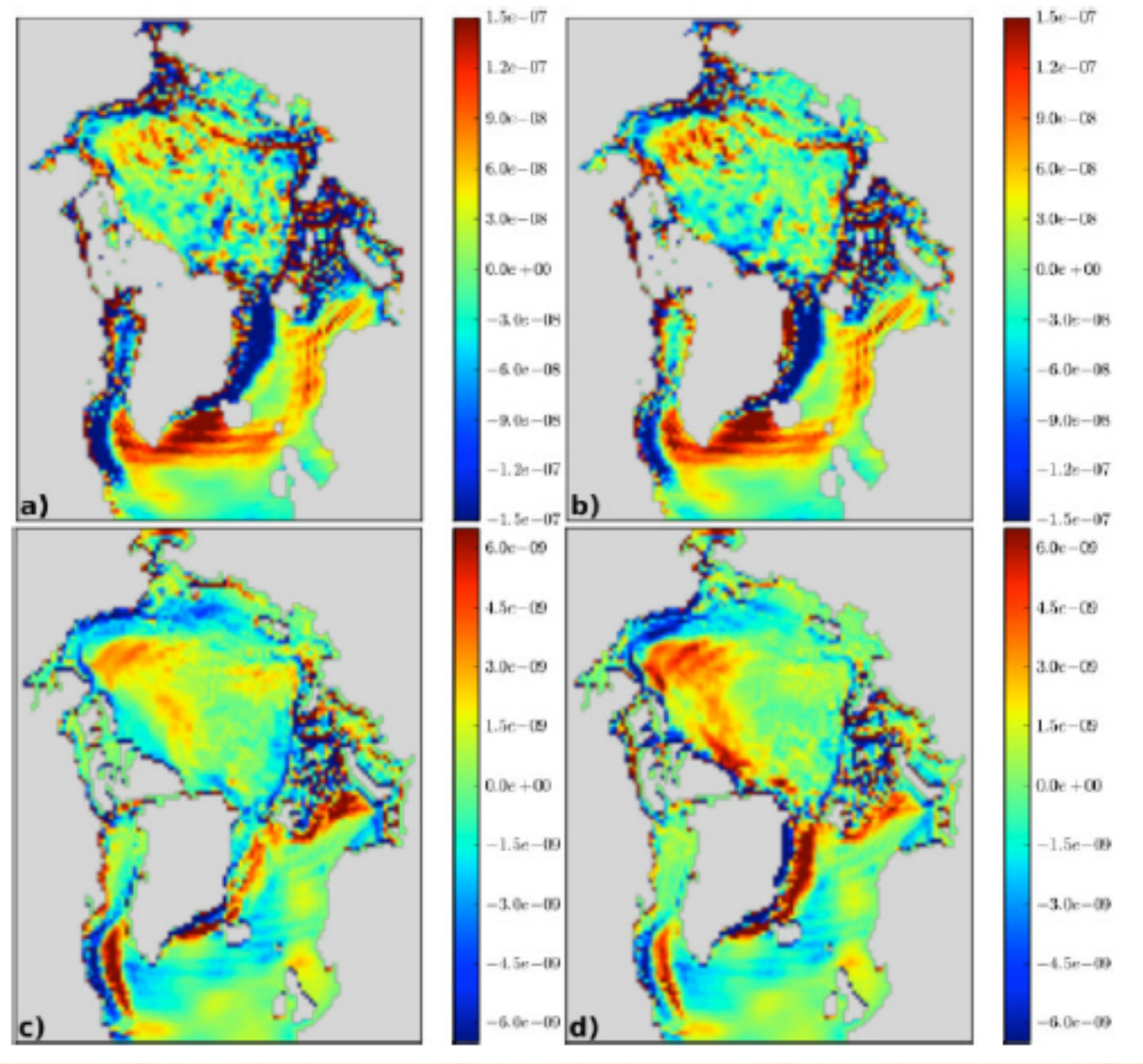


?

Trend in stress applied to ocean from ice

SKIN **FORM**



1990-2012 climatology of
Curl of ice-ocean stress
(responsible for Ekman
transport), N/m^3

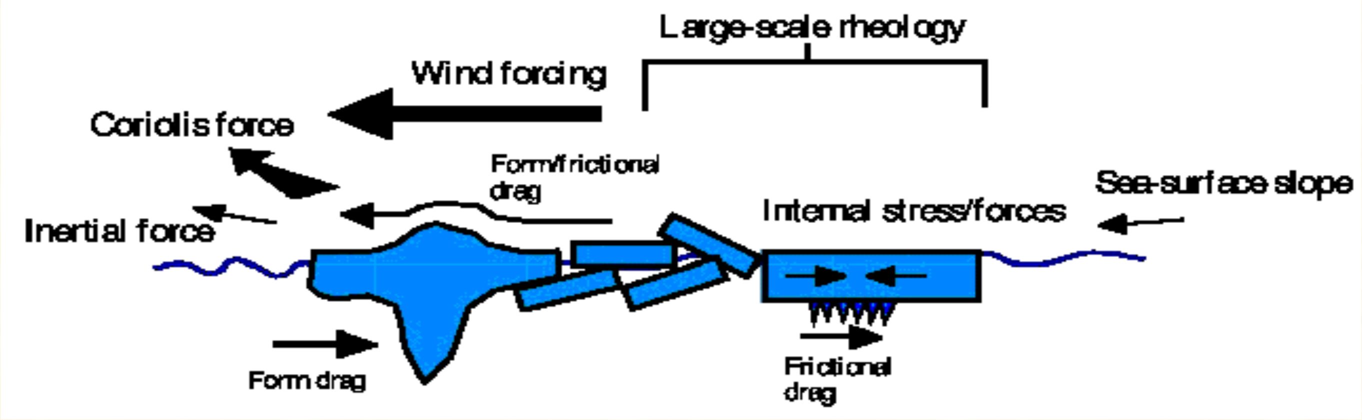
1990-2012 TREND of
Curl of ice-ocean stress
(responsible for Ekman
transport), N/m^3yr

Including FORM drag results
in **greater** ocean spin up.

Anisotropic sea ice rheology

Wilchinsky and Feltham [2006], Modelling the rheology of sea ice as a collection of diamond-shaped floes, *J. Non-Newtonian Fluid Mech.*
Tsamados, Feltham, Wilchinsky [2012], Impact of a new anisotropic rheology on simulations of Arctic sea ice, *J. Geophys. Res.*

Horizontal momentum balance of sea ice



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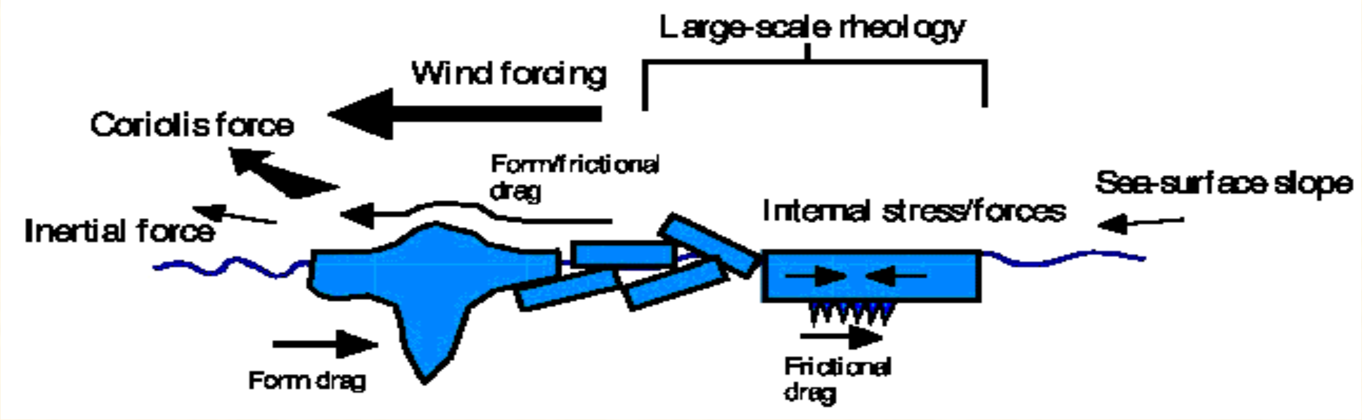

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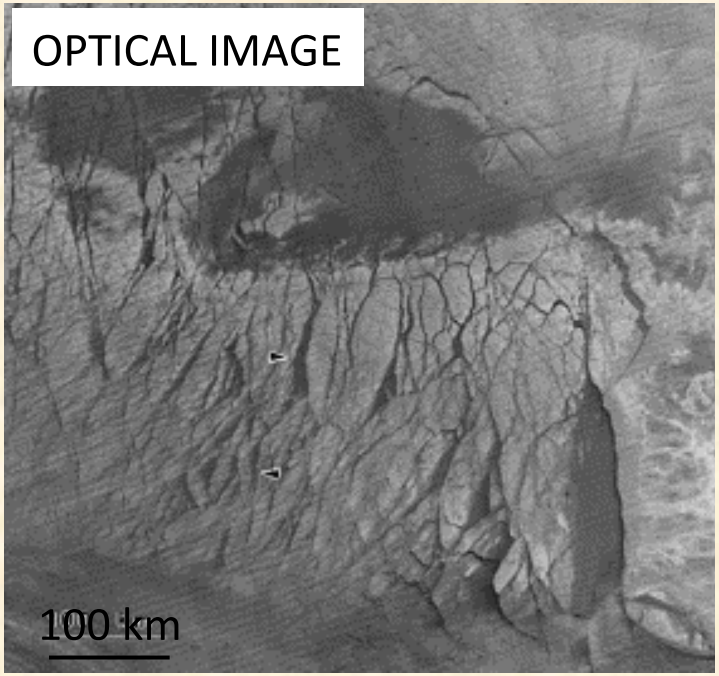
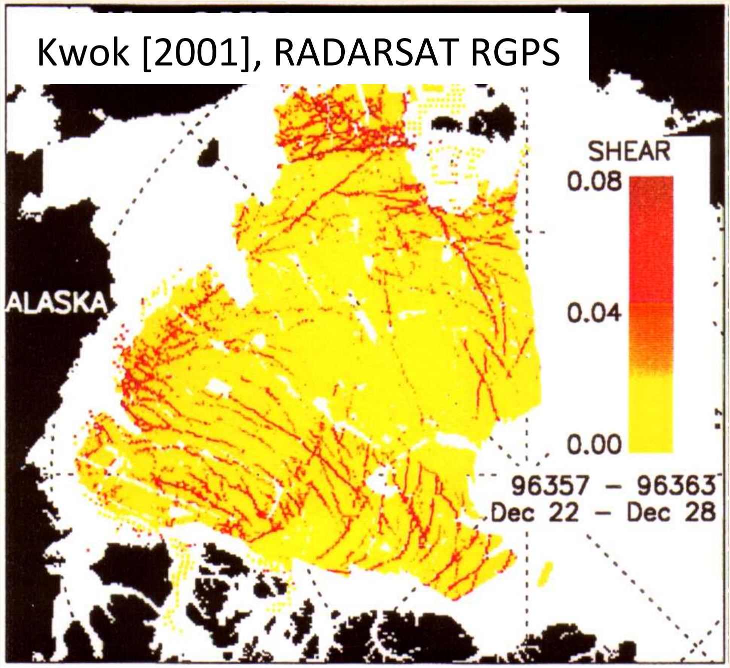
mass X acceleration = air drag + ocean drag + ice-ice force + Coriolis "force" + gravity force from sea surface tilt

$\boldsymbol{\sigma}$ is the stress caused by rupture, frictional sliding, pressure ridging, and collisions.

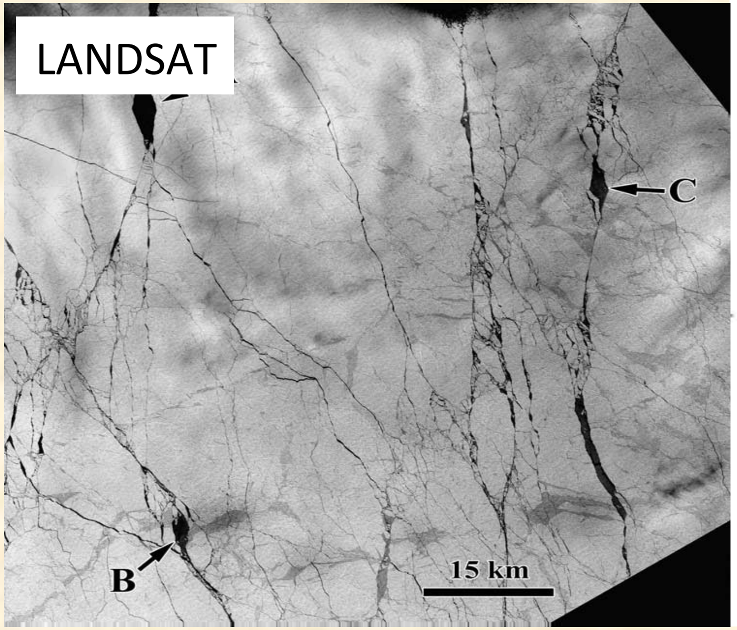
The ice-ice force, given by the *rheology* of sea ice, is poorly understood.

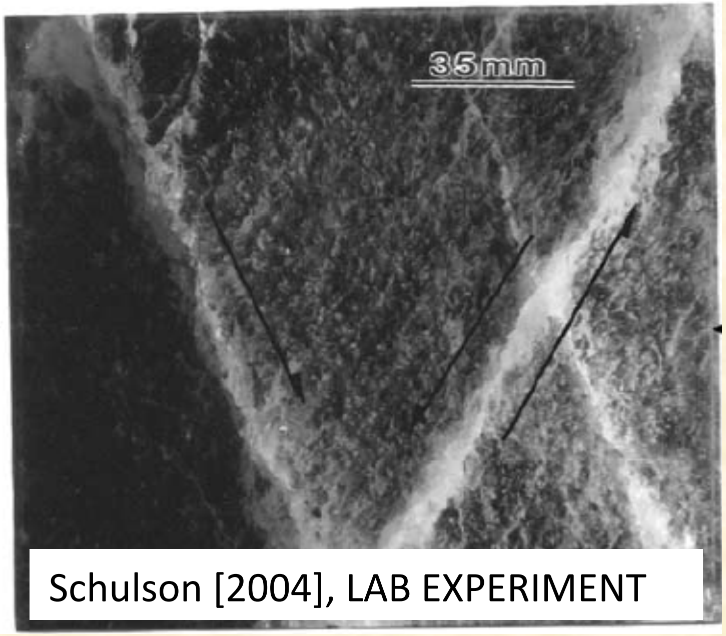
Anisotropy is present at all scales in sea ice





Linear Kinematic Features





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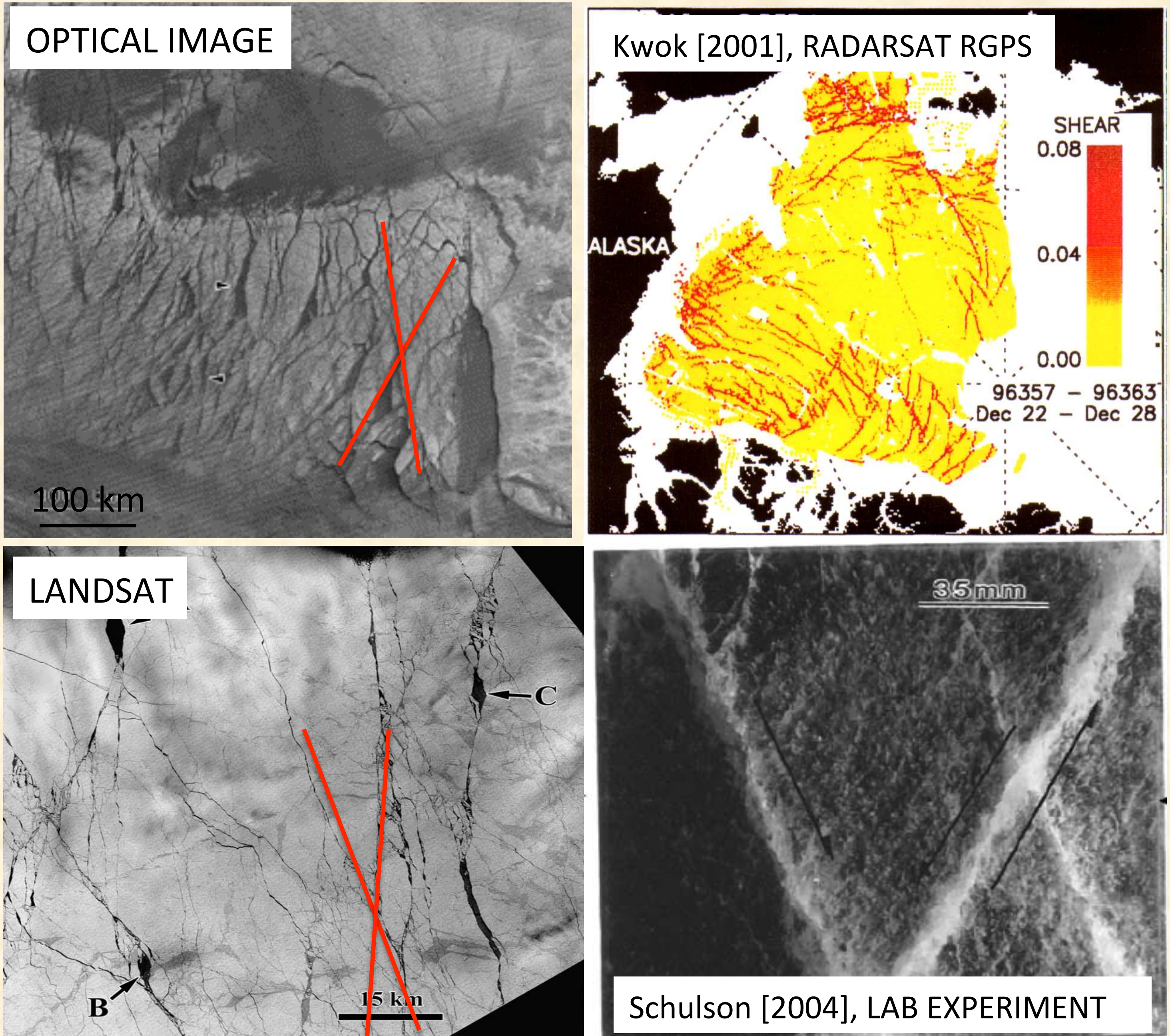

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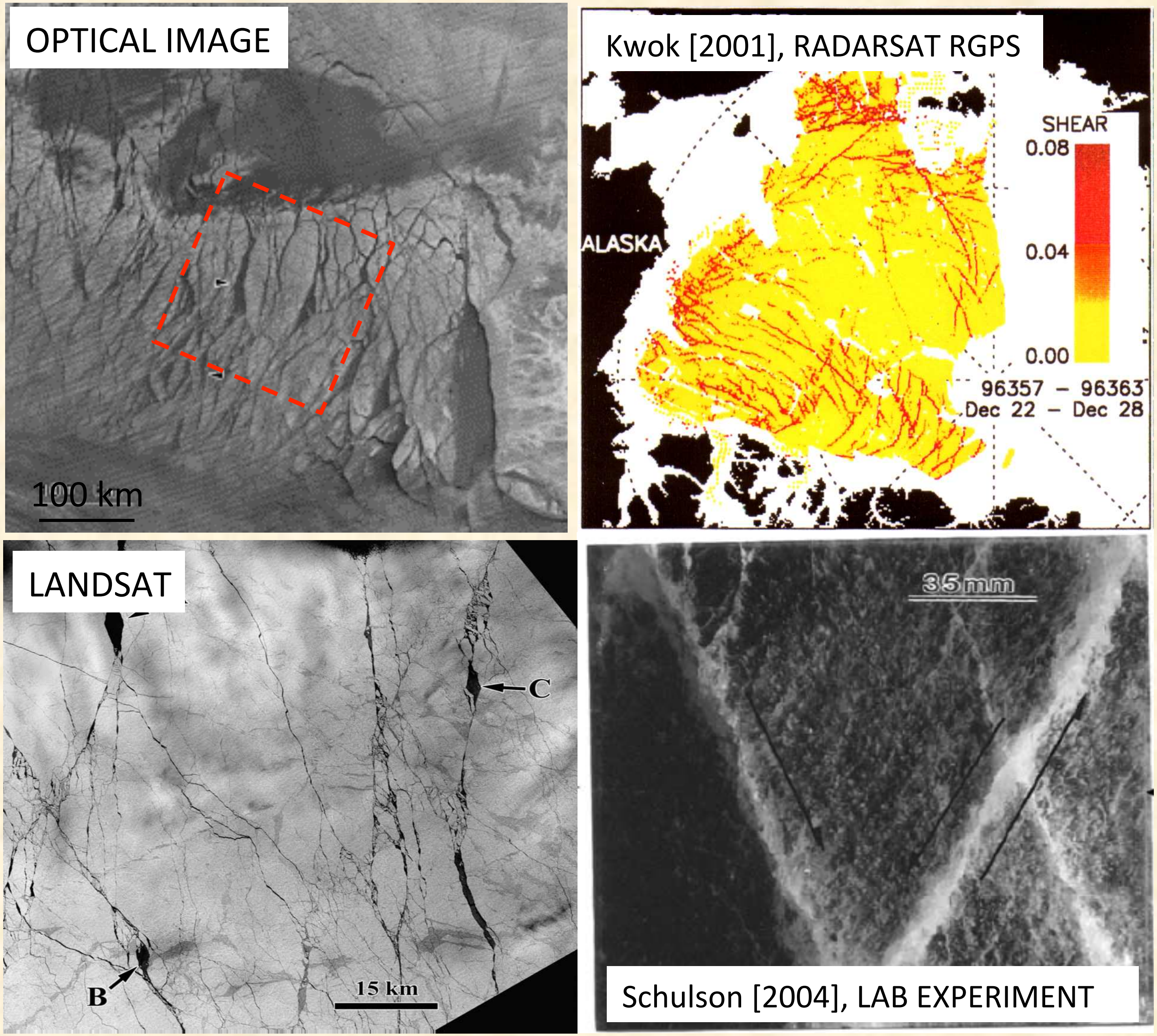

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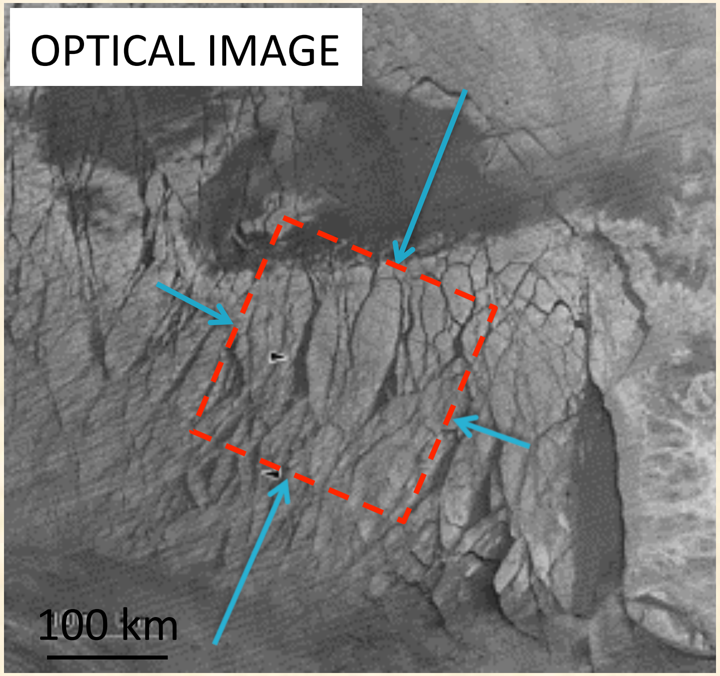

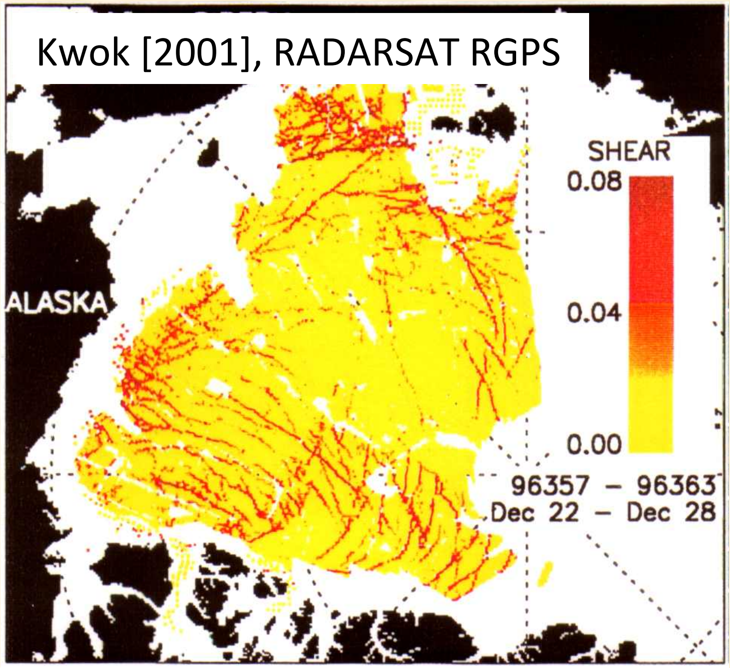

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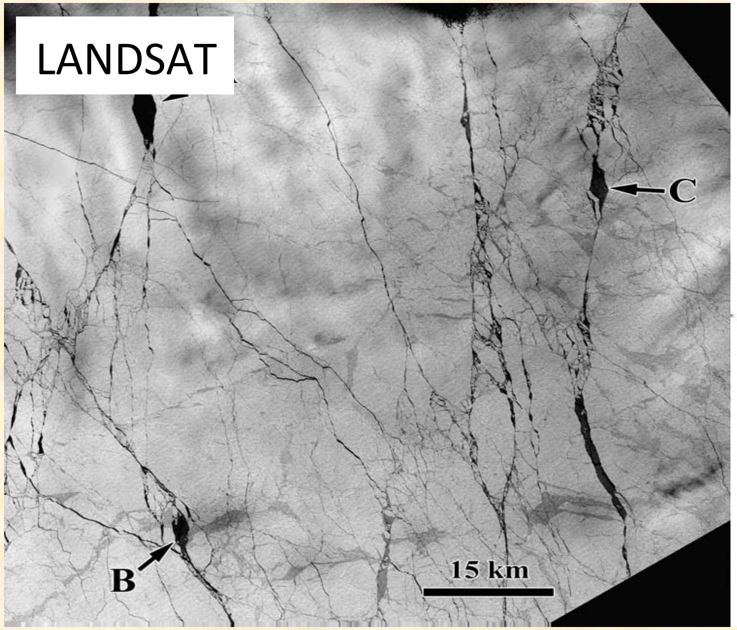
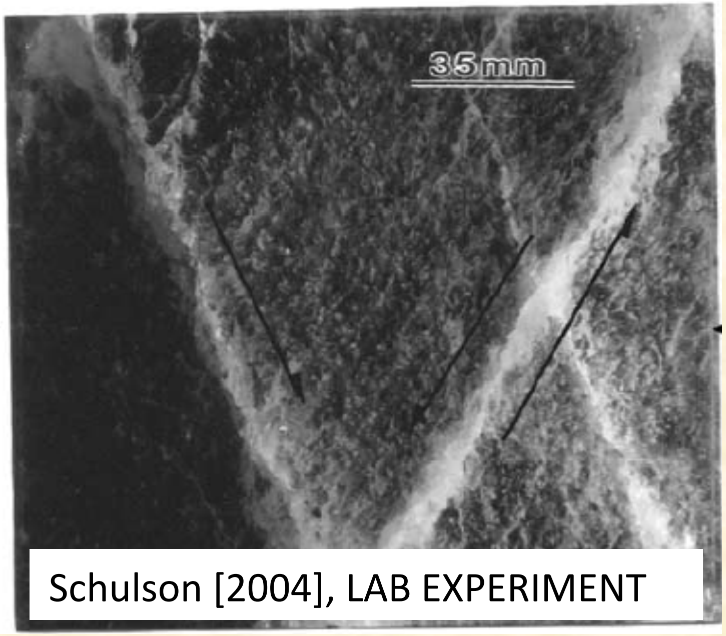




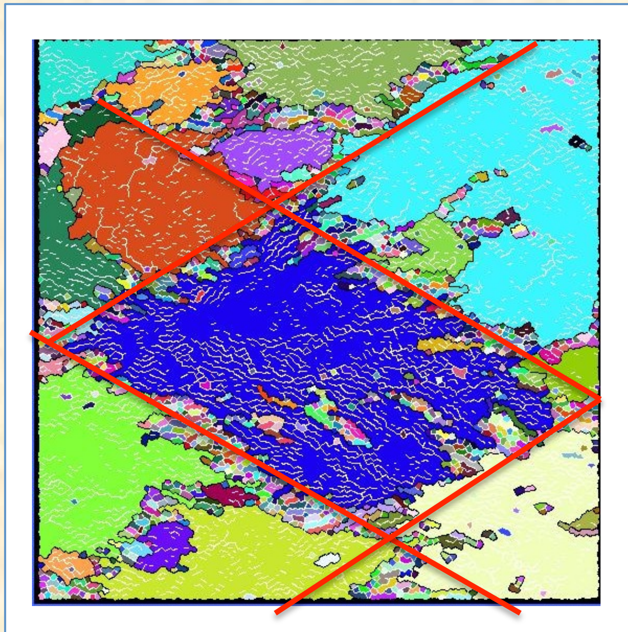
Continuum anisotropic sea ice model

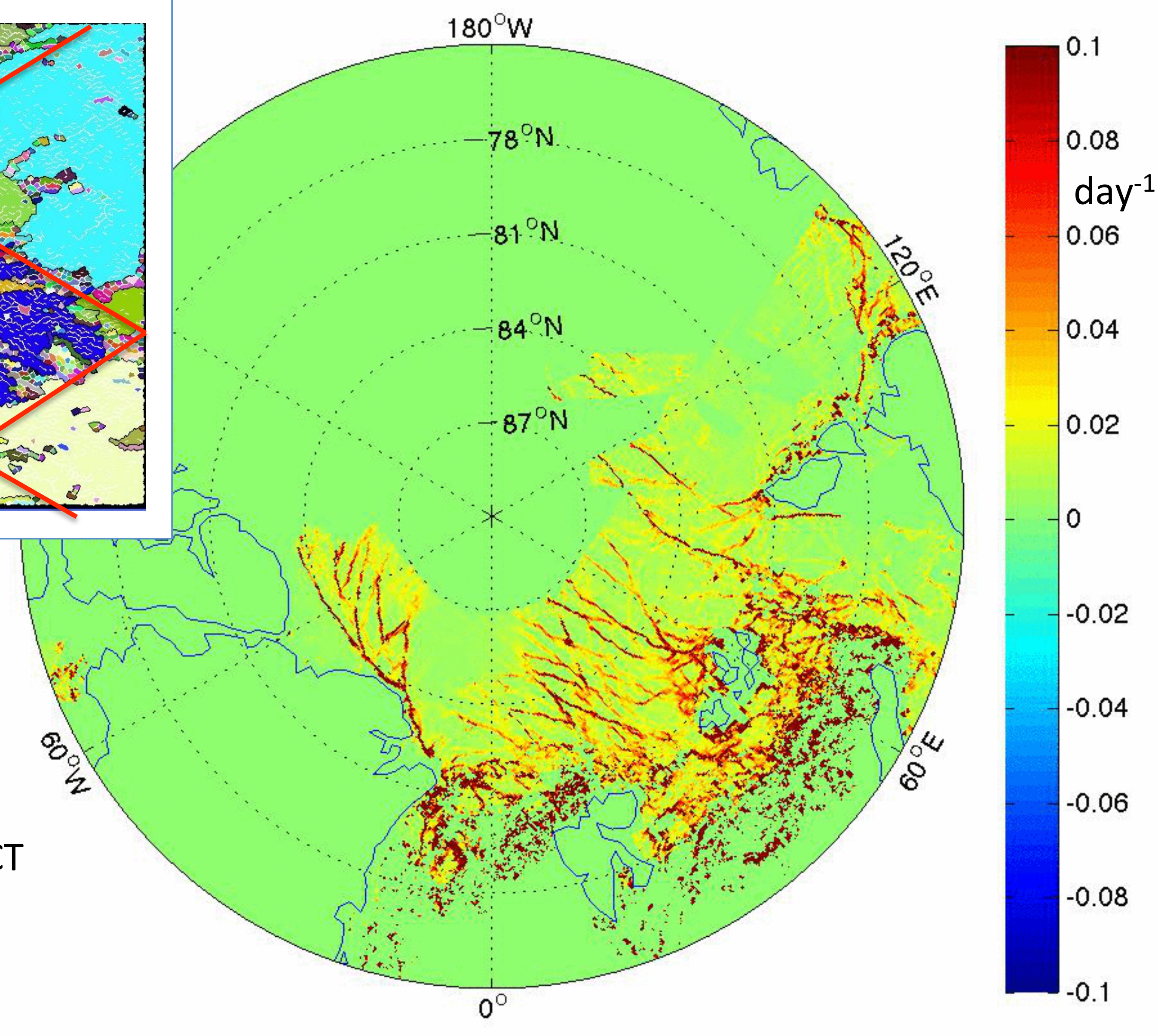
- All climate models currently assume that the ice cover is isotropic, which **observations show is wrong**.

- We developed the **Elastic-Anisotropic (EA)** continuum, anisotropic sea ice model. This model

  1. Describes anisotropy and its evolution;
  2. Relates the sea ice stress to anisotropy (rheology).

Motivation from observations: diamond-shaped floe aggregates

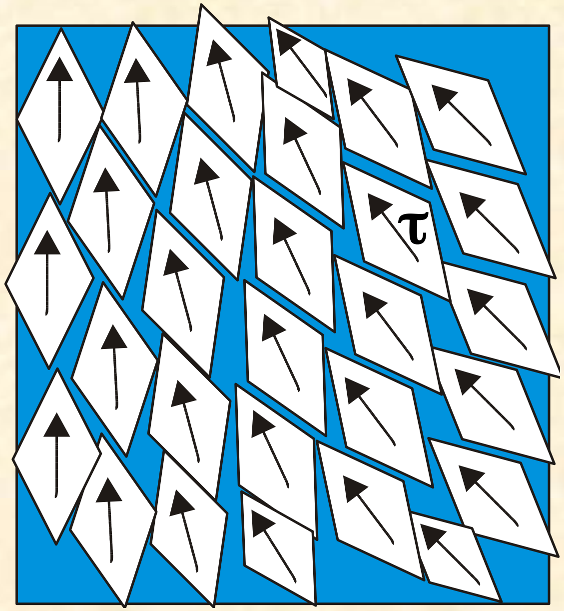




Wilchinsky et al [2010;2011]

ESA GLOBICE PROJECT
SHEAR
MARCH 2009

Simple (practical) representation of anisotropy



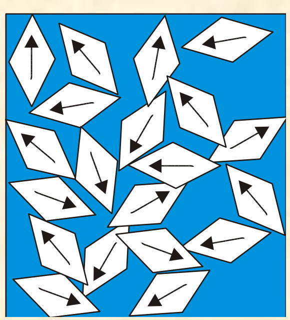
- Distribution of ice floes is given by a probability density function

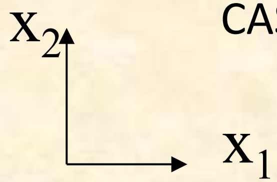
$$\Psi\left(h, w, \boldsymbol{\tau}\right)$$

- Use **internal** variables to treat anisotropy. Introduce the **structure tensor**:

$$\mathbf{A} \equiv \left\langle \boldsymbol{\tau} \otimes \boldsymbol{\tau} \right\rangle = \iiint \Psi \tau_i \tau_j \, dh\, dw\, d\boldsymbol{\tau}$$

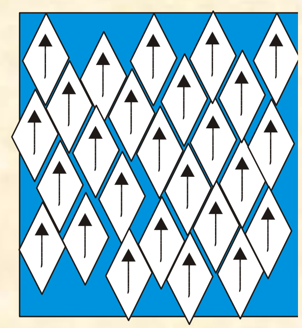
ISOTROPIC CASE:



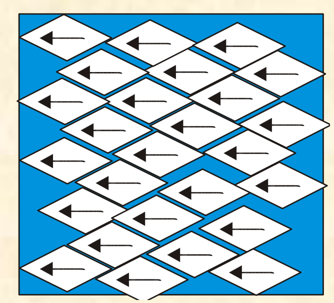


$$\mathbf{A} = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

TOTALLY ANISOTROPIC CASES:



$$\mathbf{A} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$



$$\mathbf{A} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Main processes of floe orientation change 1/2

Evolution equation for the anisotropy **A**:

$$\frac{D\mathbf{A}}{Dt} = \mathbf{F}_{therm} + \mathbf{F}_{frac}$$

Co-rotational derivative
(includes rigid body rotation)

As floes freeze together, or melt apart, the ice cover becomes more isotropic:

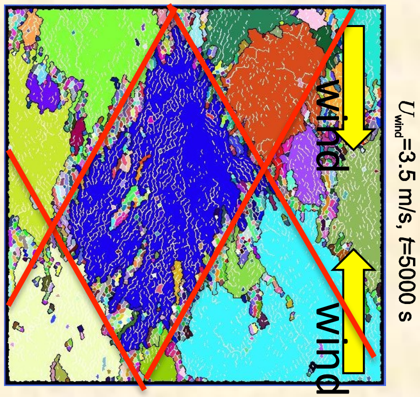
$$\mathbf{F}_{therm} = -k_{therm}\left(\mathbf{A} - \frac{1}{2}\mathbf{1}\right)$$

Main processes of floe orientation change 2/2

Evolution equation for the anisotropy **A**:

$$\frac{D\mathbf{A}}{Dt} = \mathbf{F}_{therm} + \mathbf{F}_{frac}$$

Co-rotational derivative
(includes rigid body rotation)

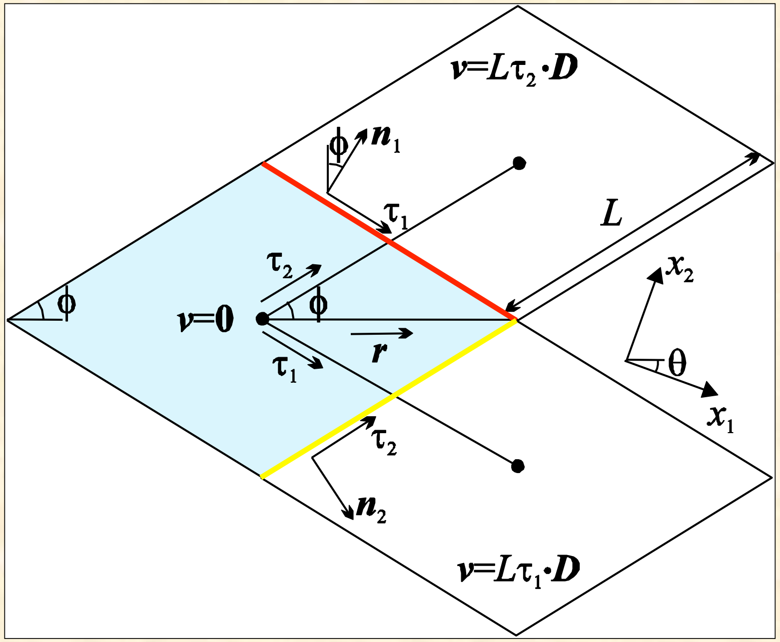


Under biaxial or uniaxial compression, new cracks form, either to form conjugate cracks (Coulombic) or axial faults (ridges). In either case, the ice cover becomes more anisotropic:

$$\mathbf{F}_{frac}(\mathbf{A};\boldsymbol{\sigma}) = -k_{mech}(\mathbf{A} - \mathbf{S})$$

where **S** reflects the new preferred orientation of cracks.

Determination of anisotropic sea ice rheology $\sigma(D, h; A)$



- Determination of mean floe stress from edge tractions due to ridging or sliding.

Edge tractions on floe:

$$\mathbf{F}_1 = -\mathrm{He}\left(-\mathbf{D}:\mathbf{n}_1\boldsymbol{\tau}_2\right)F_r\mathbf{n}_1 + \mathrm{sgn}\left(-\mathbf{D}:\boldsymbol{\tau}_2\boldsymbol{\tau}_1\right)\mathrm{He}\left(-\mathbf{D}:\boldsymbol{\tau}_2\mathbf{n}_1\right)F_s\boldsymbol{\tau}_1$$

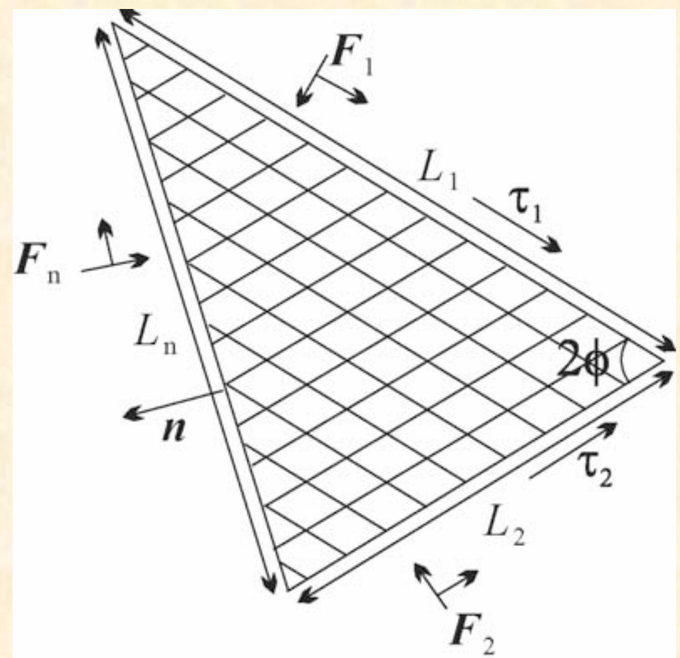
$$\mathbf{F}_2 = -\mathrm{He}\left(-\mathbf{D}:\mathbf{n}_2\boldsymbol{\tau}_1\right)F_r\mathbf{n}_2 + \mathrm{sgn}\left(-\mathbf{D}:\boldsymbol{\tau}_2\boldsymbol{\tau}_1\right)\mathrm{He}\left(-\mathbf{D}:\boldsymbol{\tau}_1\mathbf{n}_2\right)F_s\boldsymbol{\tau}_2$$

F_r is the normal ridging force; F_s is the tangential sliding force.
Forces only active when edges are compressed
(the Heaviside functions become unity).

Mean stress theorem yields

$$L_1\mathbf{F}_1 + L_2\mathbf{F}_2 + L_n\mathbf{F}_\mathbf{n} = \mathbf{0} + \underbrace{O\left(L_1L_2\right)}_{\approx\,\mathbf{0}}$$

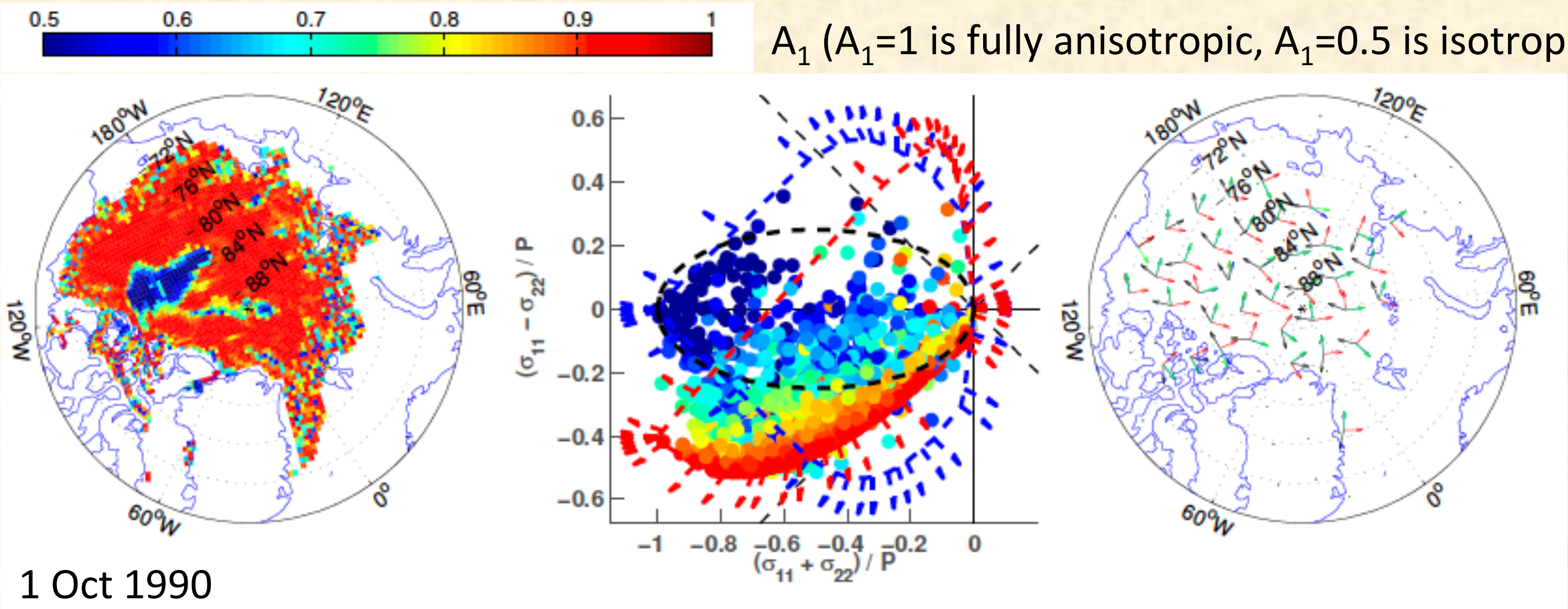
Edge tractions dominate body/inertial forces



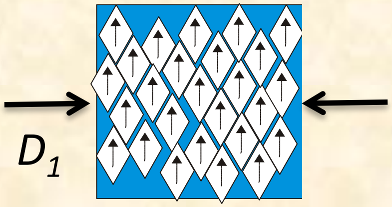
This yields the normal traction (after algebra)

$$\mathbf{F}_\mathbf{n} = \frac{1}{\sin\phi}\left[\mathbf{F}_1\boldsymbol{\tau}_2 + \mathbf{F}_2\boldsymbol{\tau}_1\right]\cdot\mathbf{n} \equiv \boldsymbol{\sigma}_\mathbf{a}\cdot\mathbf{n}$$

First anisotropic climate sea ice model

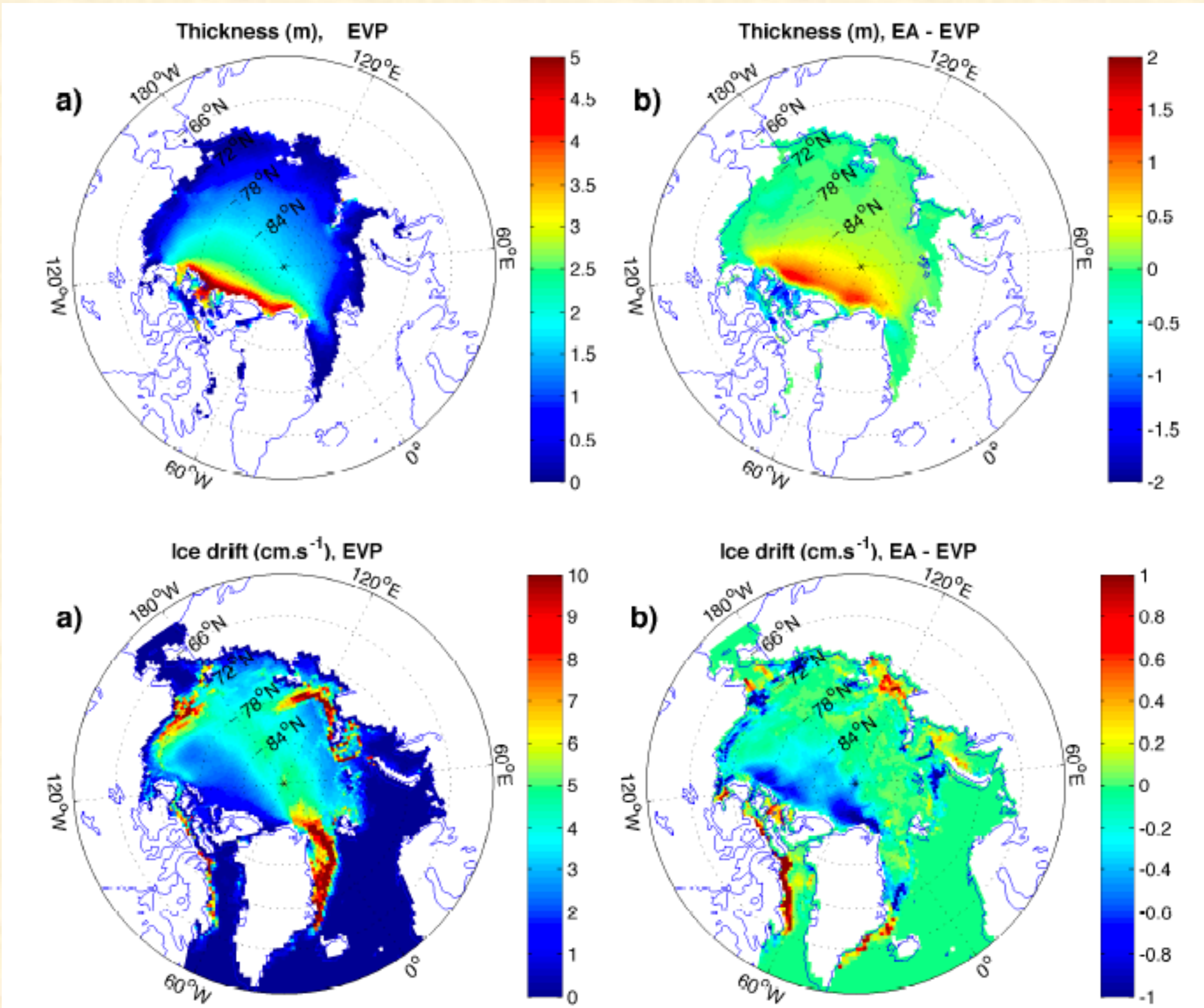


- Under realistic forcing, ice cover is **mainly anisotropic** and this evolves on the **wind pattern timescale**
- Anisotropy produces **large shear stresses** (“fat” yield curve)
- Major principal axes of structure tensor and deformation rate are orthogonal



Arctic sea ice state – September average 1990-2007

ISOTROPIC RHEOLOGY **ANISOTROPIC - ISOTROPIC**



The Elastic Anisotropic (EA) model is tuned to have same compressive isotropic strength as the standard (EVP) isotropic model.

Thus impacts shown here are **conservative**.

30% more ice with EA

Summary remarks

- **Observations** show the sea ice cover is **anisotropic**.
- We have developed the **first anisotropic sea ice climate model** and have included this into the latest release of CICE (late 2013) that is part of several IPCC GCMs.
- Including anisotropy accounts for a **range** of yield behaviours (yield curves) and **affects the mass budget and flow to leading order**.
- We believe anisotropy results in a more realistic **thickness distribution** and **mass flux** to lower latitudes.
- Assessment of impact of anisotropy on climate sea ice simulations is ongoing.

Melt ponds

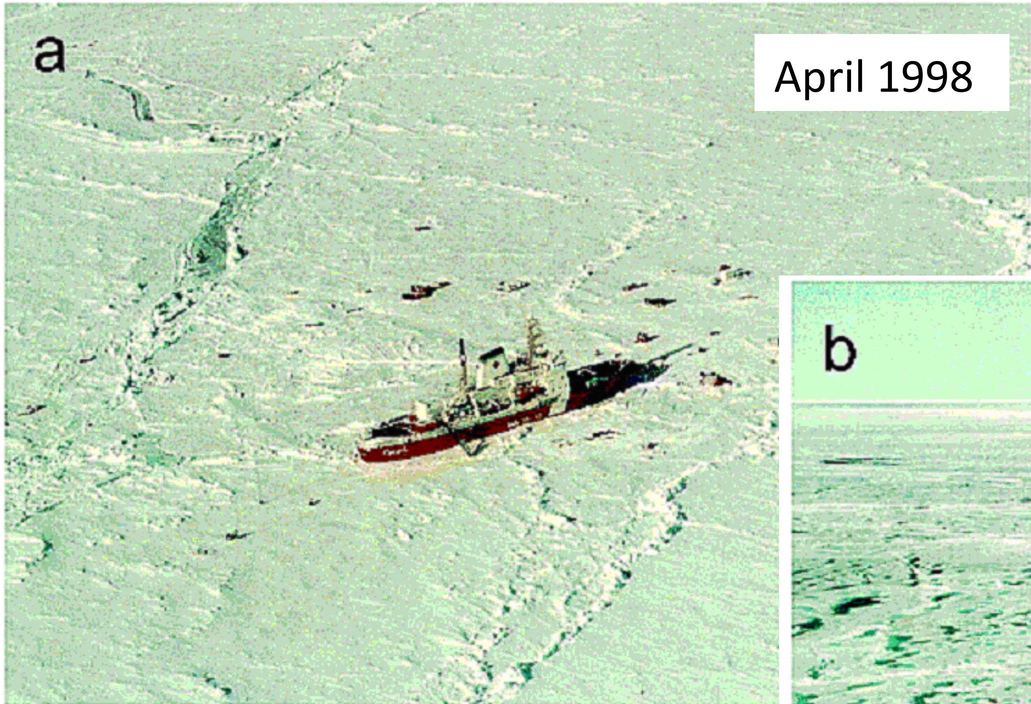
Flocco, Schroeder, Feltham, and Hunke [2012], Impact of melt ponds on Arctic sea ice simulations from 1990 to 2007, *J. Geophys. Res.*

Schroeder, Feltham, Flocco, and Tsamados [2014], September Arctic sea-ice minimum prediction by spring melt-pond fraction, *Nature Climate Change*

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. Ponds are typically 1-100m wide and 0.1-1.5m deep.
- 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)
- Deeper ponds have a lower albedo, which saturates at about 1.5m depth.
- 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.**

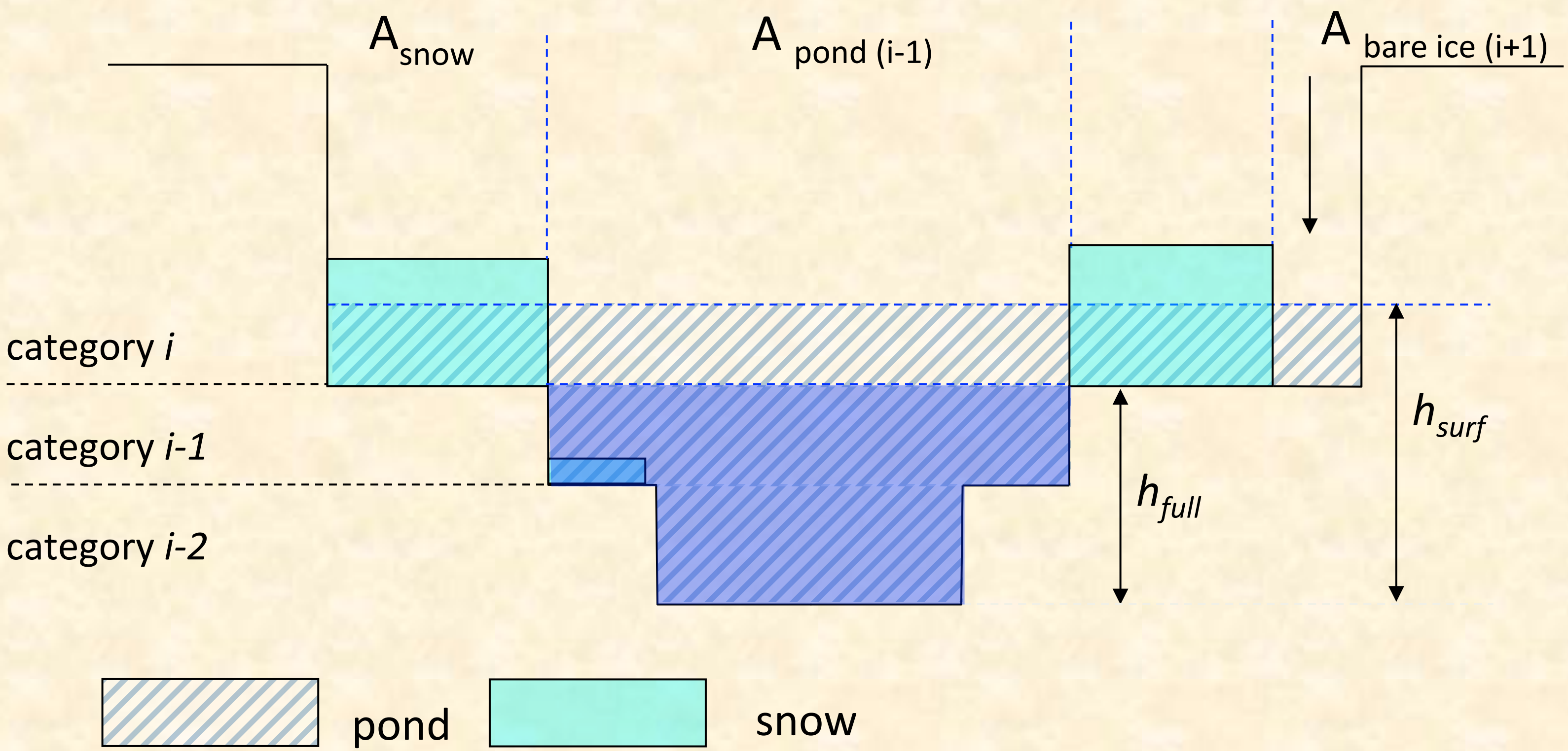
GCM-compatible melt pond model

[Flocco and Feltham, 2007]

Main difficulty with including melt ponds into a GCM is lack of surface topography.

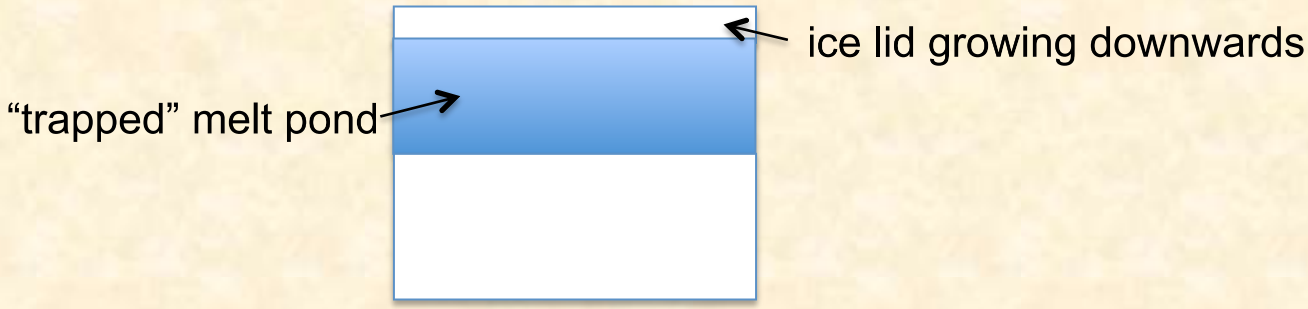
As a partial fix, we introduced a surface height *α(h)* distribution, which gives the relative area of ice of a given surface height.

We let melt water fill up the surface, which determines the pond area and depth.

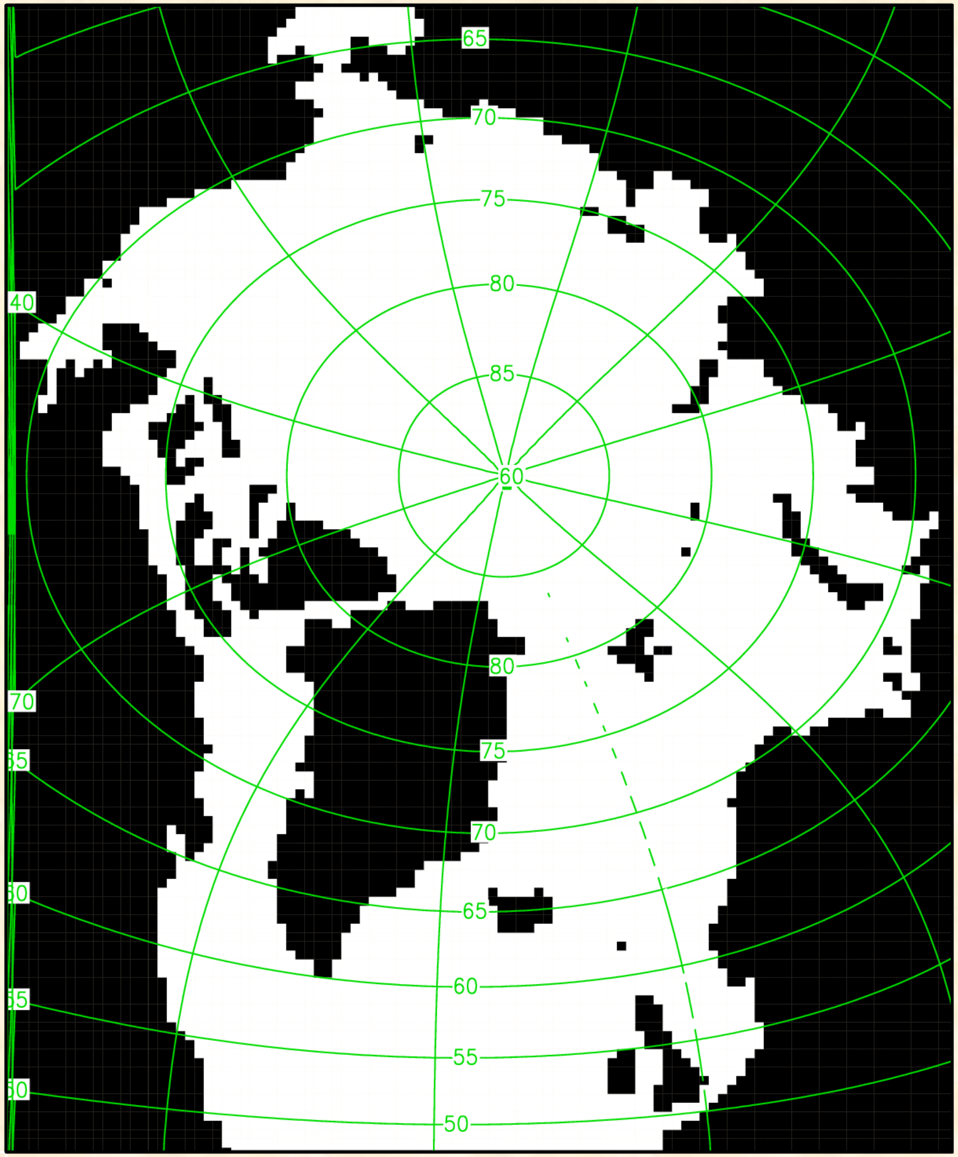


Melt pond parameterisation features

- 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.



CPOM sea ice simulation with our pond scheme

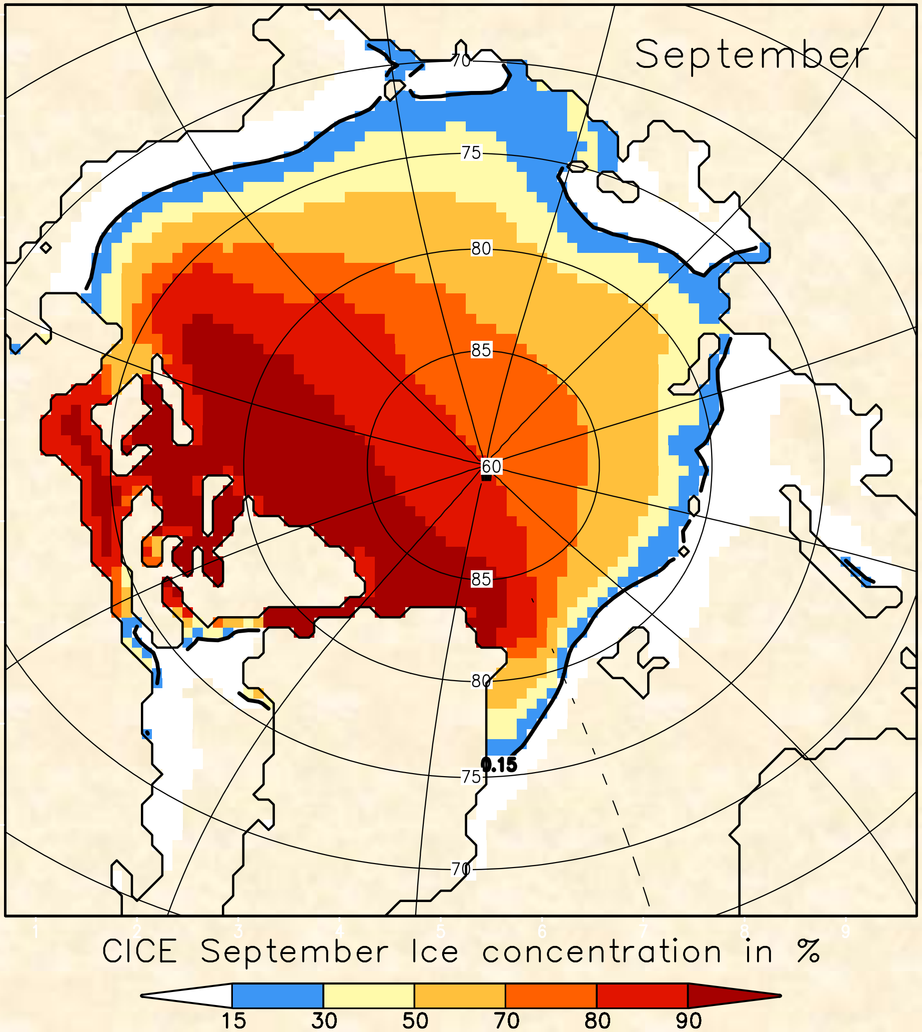


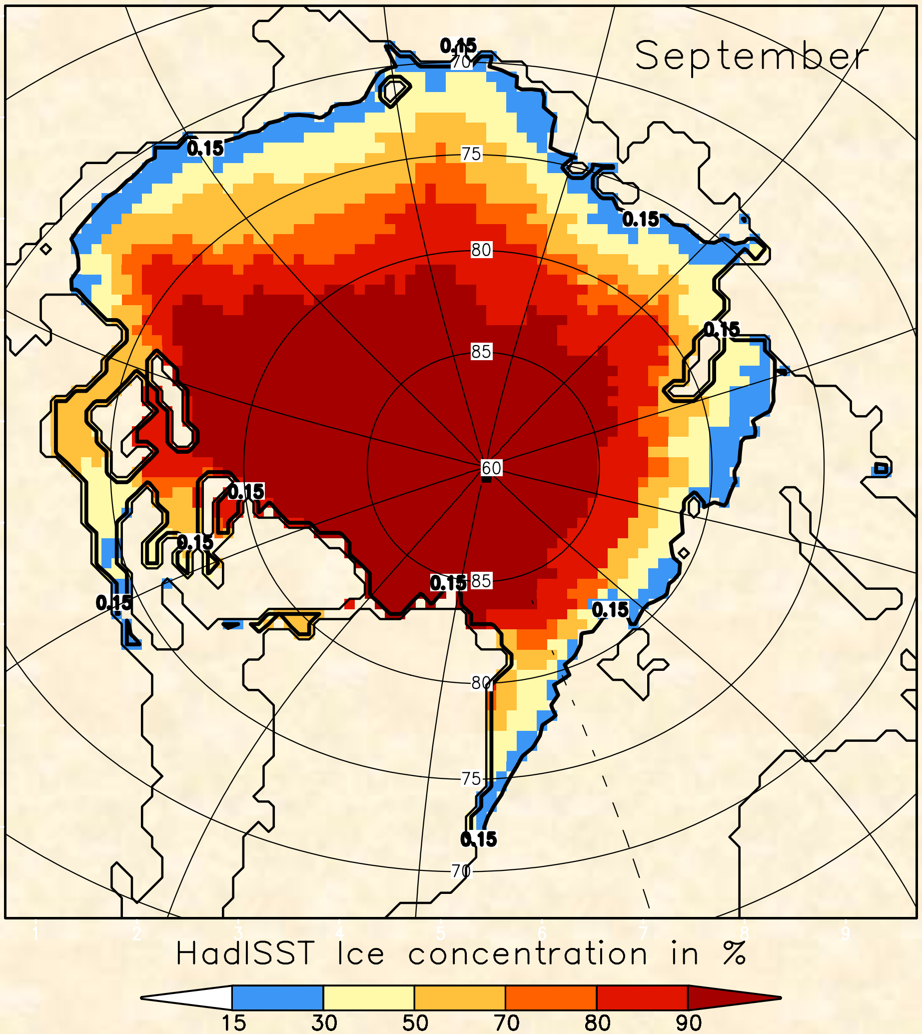
- Based on the CICE model used by the Met Office
- Stand-alone (1979-2013)
- Arctic domain (40 km)
- Atmosphere:
  - T2m, q2m (6-hourly)
  - u10m, v10m (6-hourly)
  - QLW, QSW (daily)
  - PRECIP, SNOW (monthly)

  (**NCEP2**, **ERA-Interim**, **DRAKKAR DFS5**)
- Ocean:
  - Mixed-layer ocean (20 m)
  - SO1m, TO1m (clim. monthly means)
  - SO prescribed, TO prognostic, 20d restoring

  (Reading Ocean-Reanalysis)

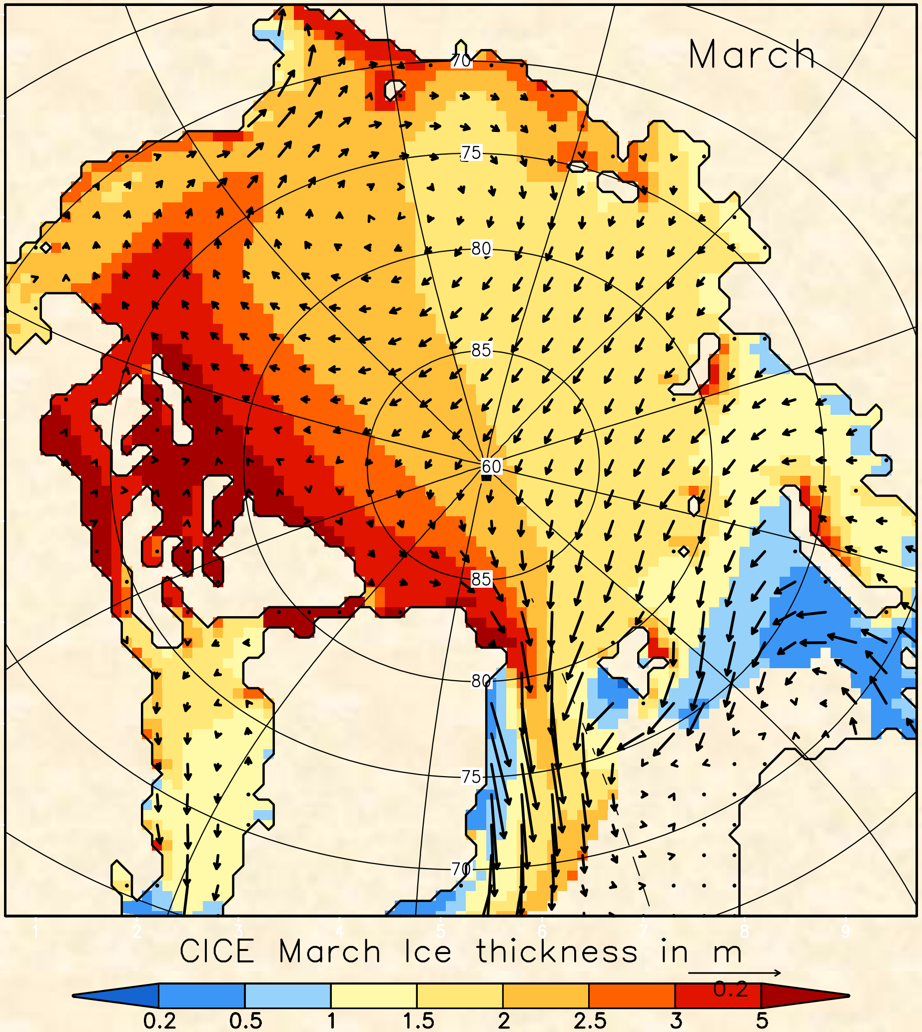
Climatology 1979-2012 September Ice Concentration



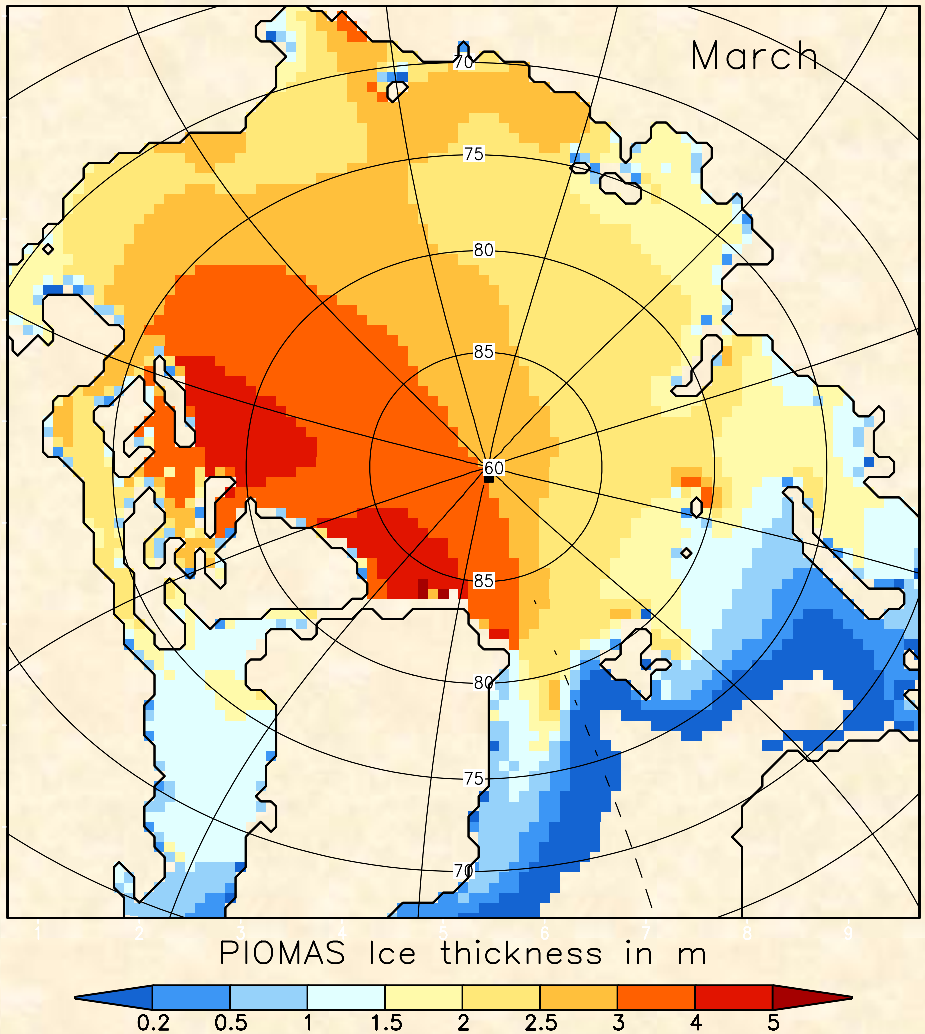


Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST)

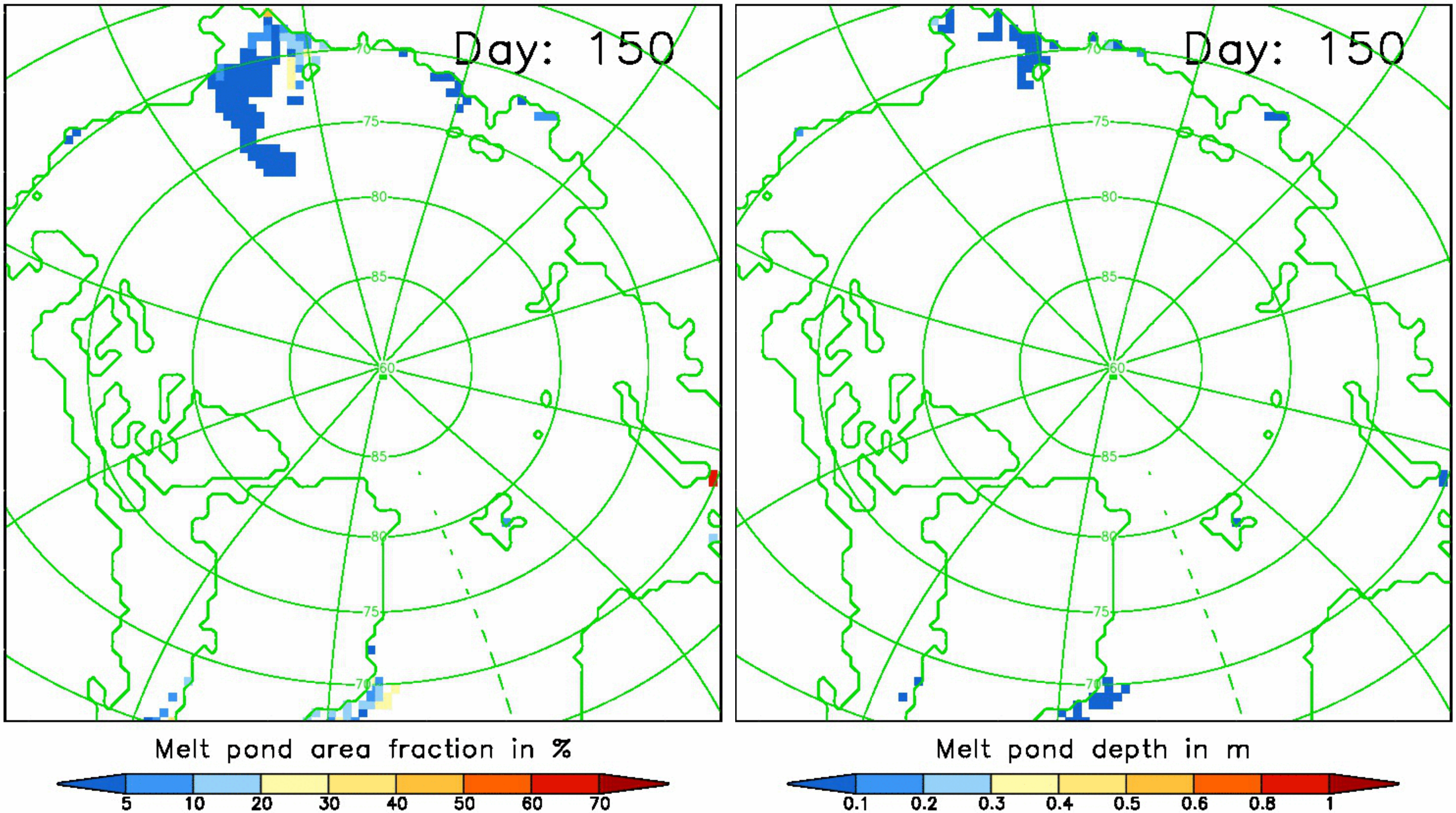
Climatology 1979-2012 March Ice Thickness

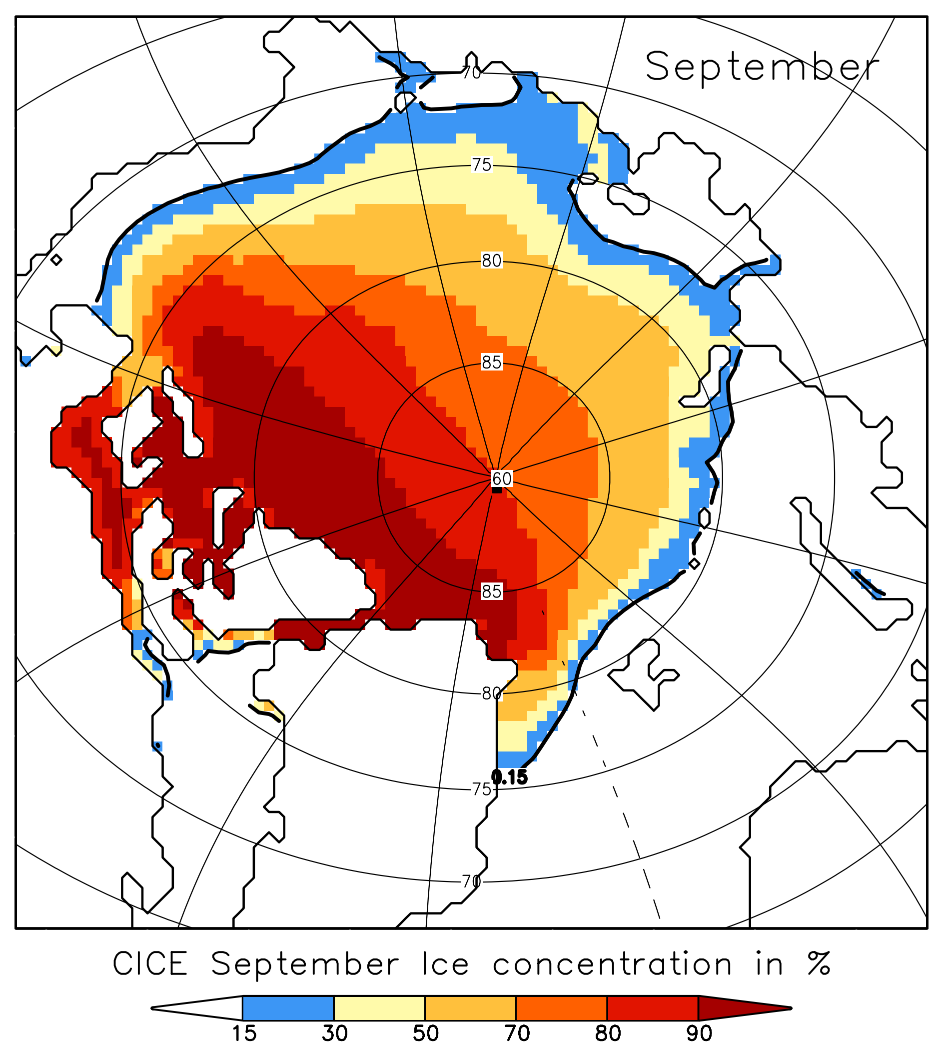


PIOMAS (Pan-Arctic Ice-Ocean Modeling and Assimilation System) Data Sets – from the Retrospective Investigation [c.f. CryoSat2, Laxon et al 2013]



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



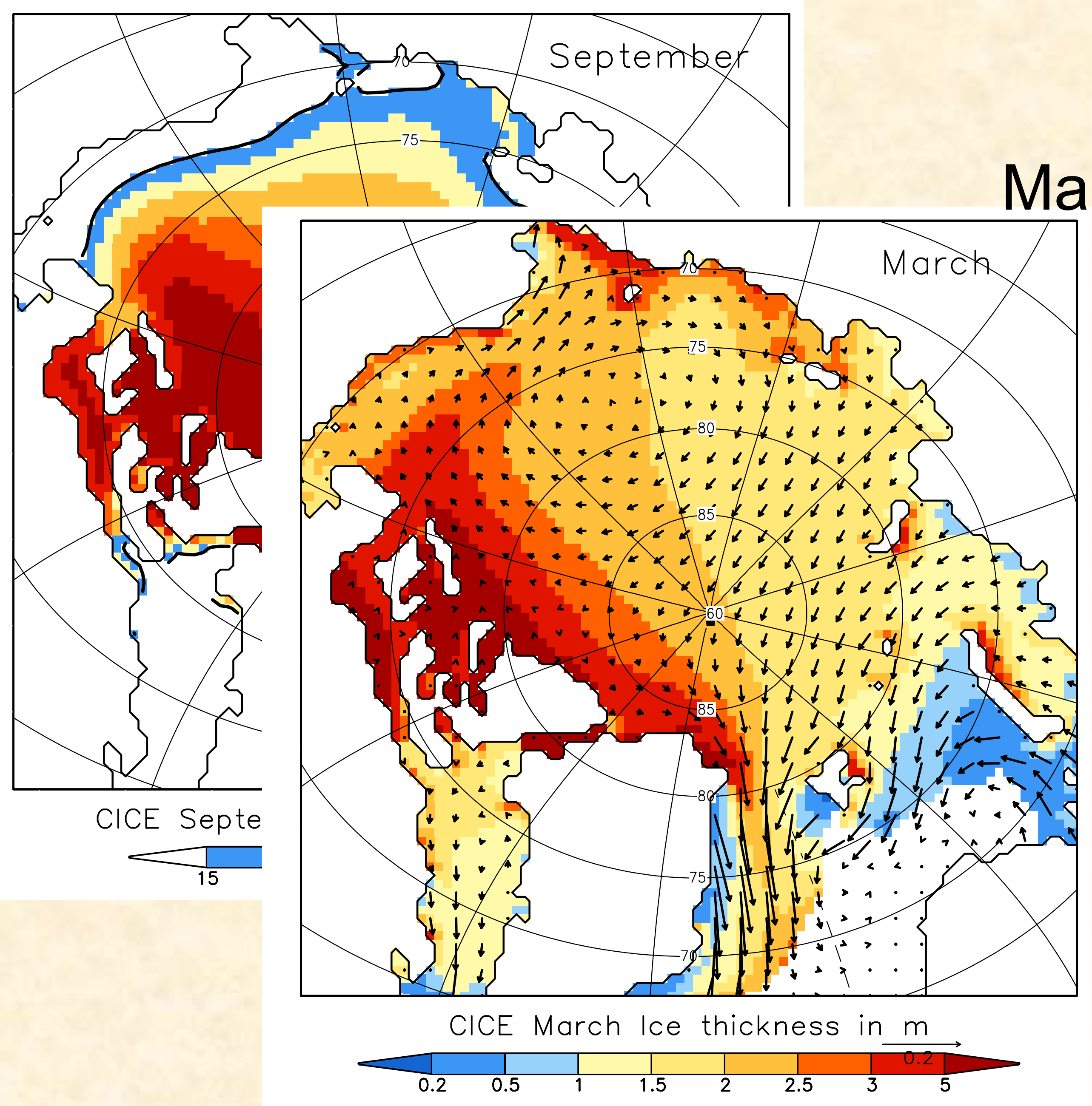


Climatology 1979-2012 September Ice Concentration

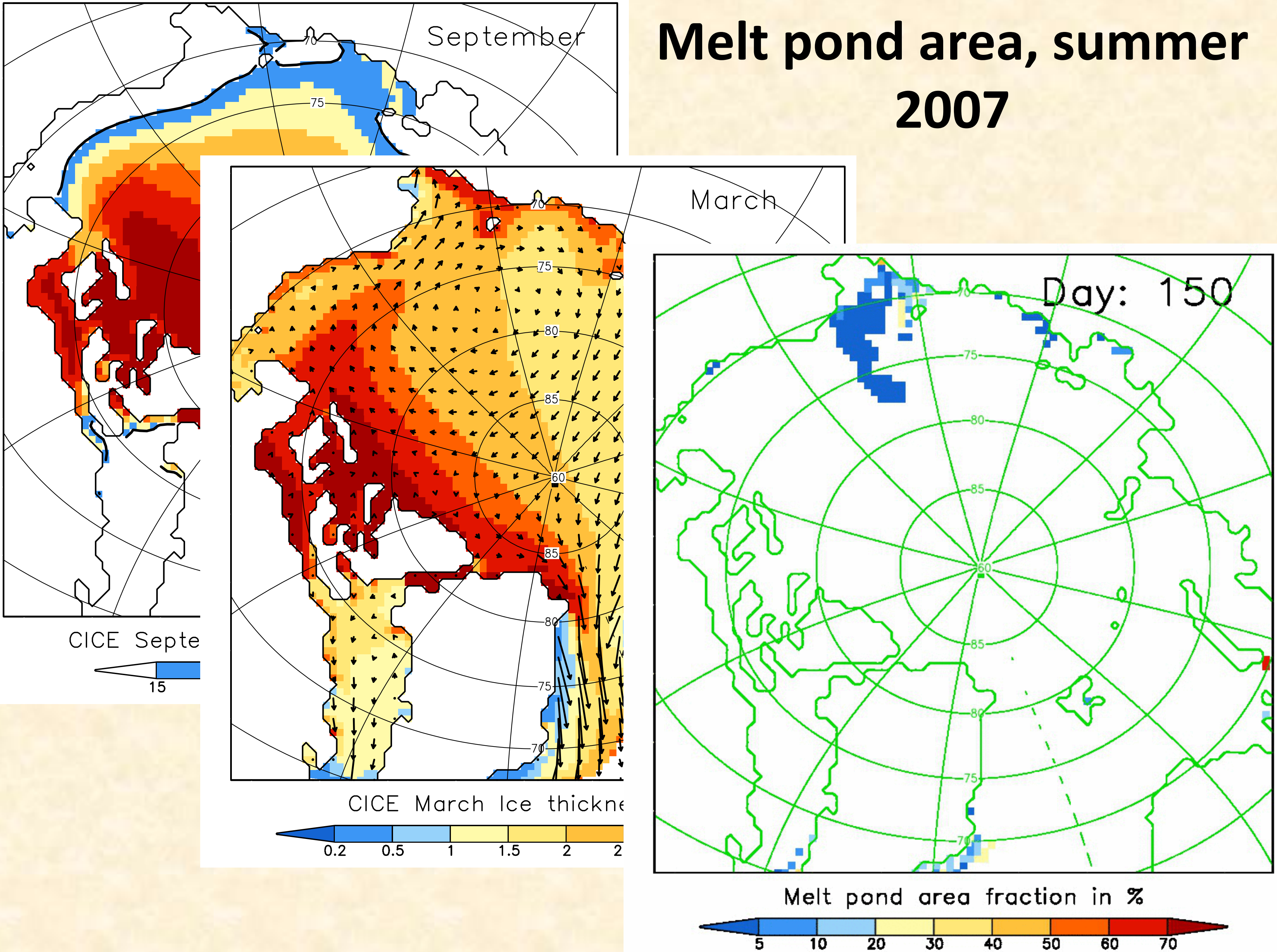
Stand-alone, i.e. forced, sea ice model including our pond scheme.

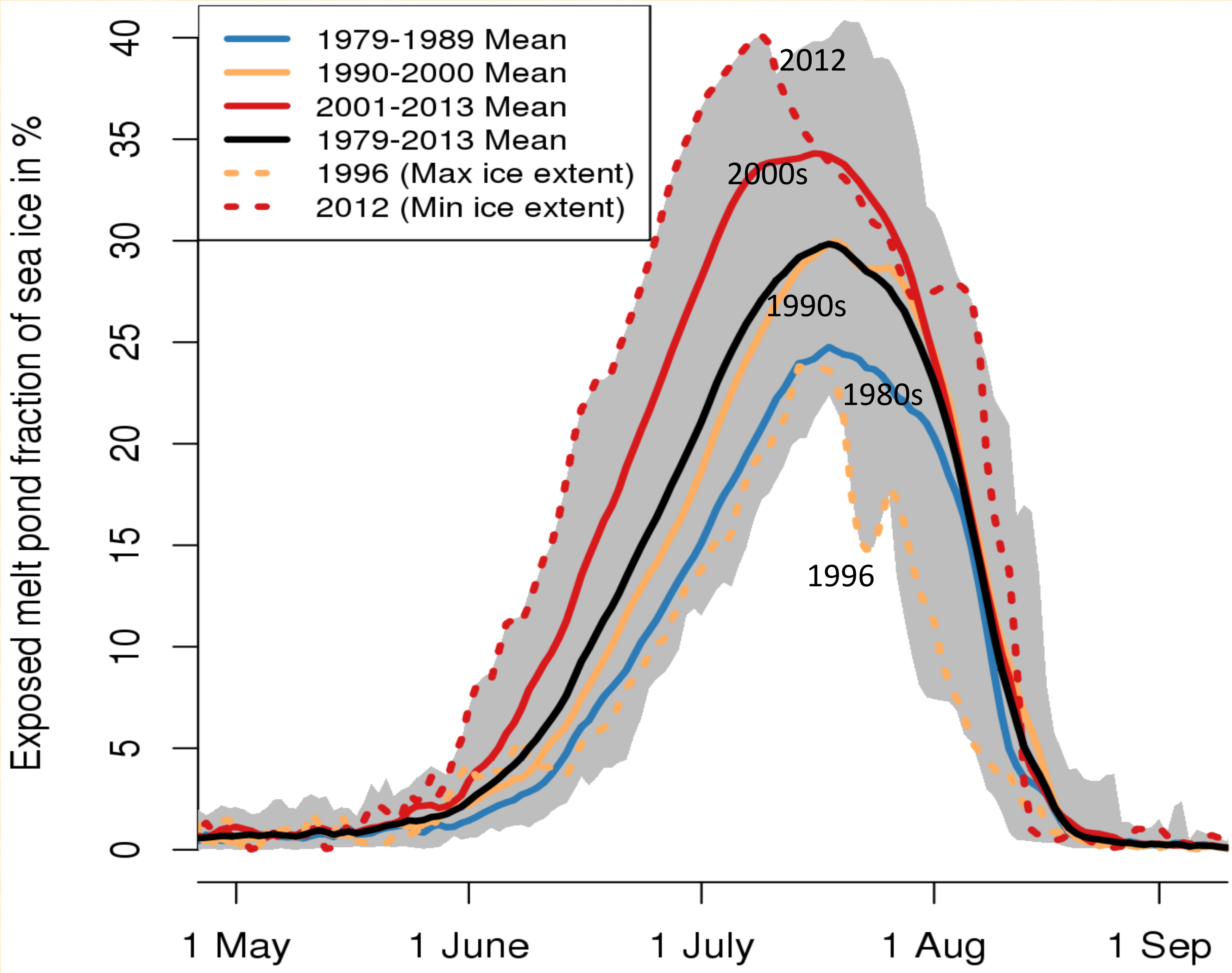
Climatological sea ice concentration and thickness are reasonable compared with observations (HadISST and PIOMAS).

Climatology
1979-2012
March Ice Thickness



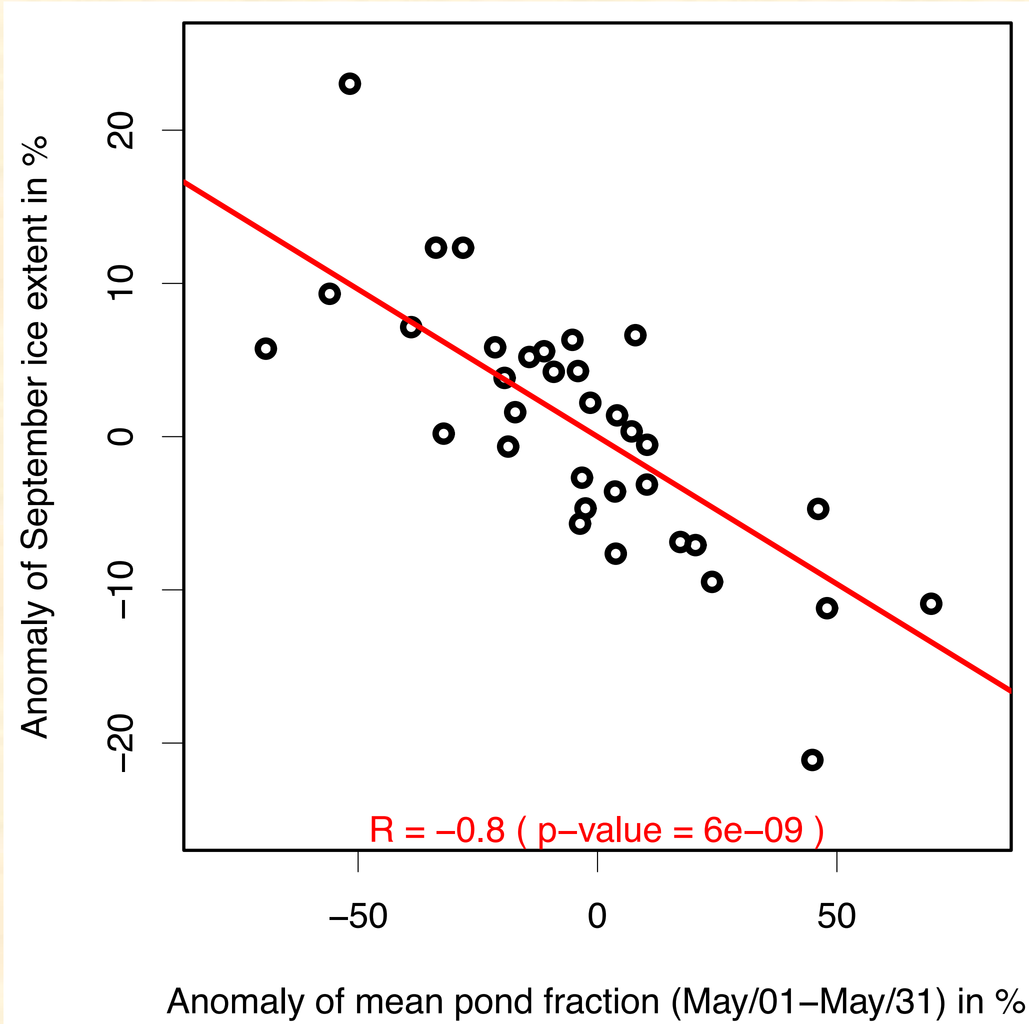
Melt pond area, summer 2007





1979-1989 Mean
1990-2000 Mean
2001-2013 Mean
1979-2013 Mean
1996 (Max ice extent)
2012 (Min ice extent)
2012
2000s
1990s
1980s
1996
Exposed melt pond fraction of sea ice in %
0
5
10
15
20
25
30
35
40
1 May
1 June
1 July
1 Aug
1 Sep

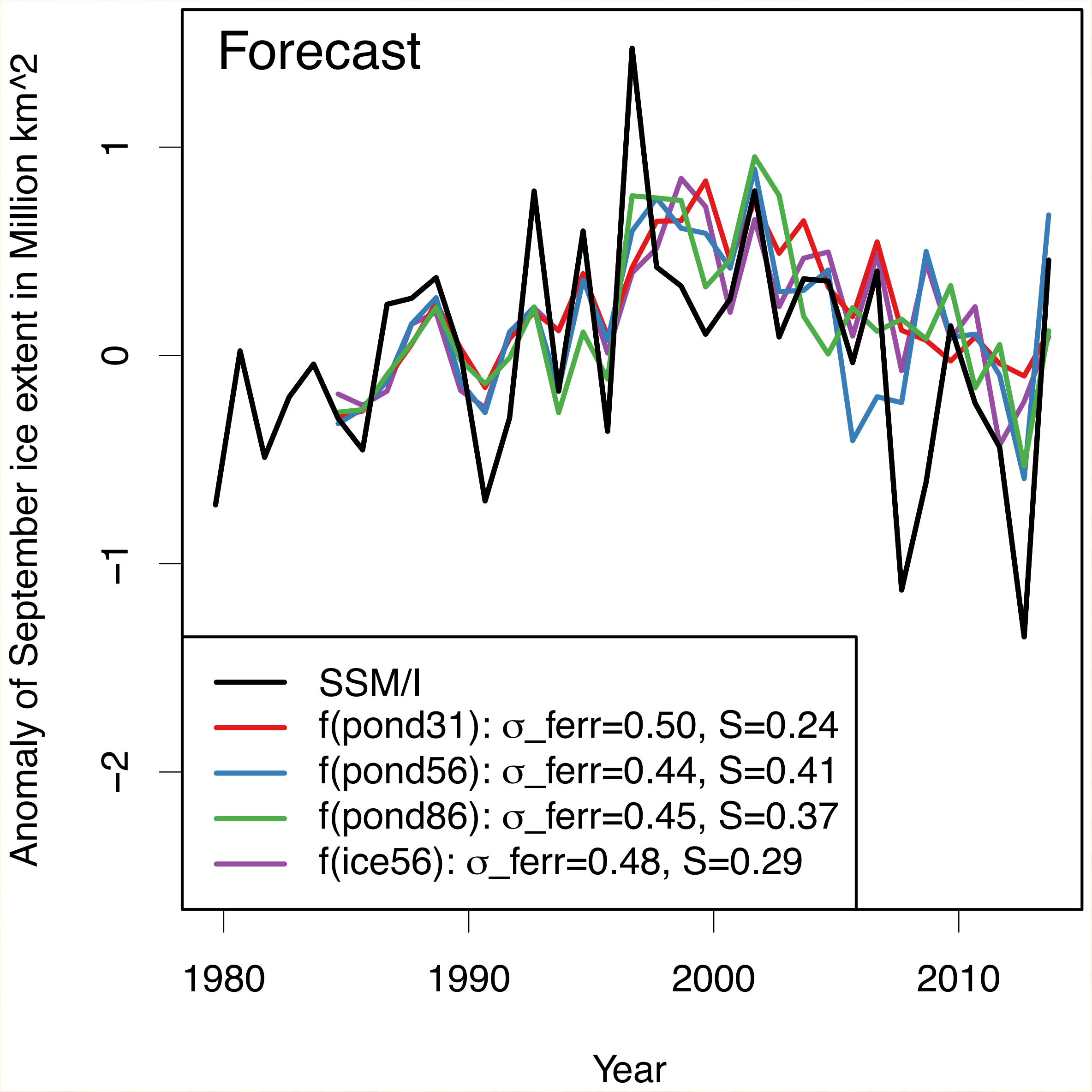
Correlation of September sea ice minima with pond fraction in May



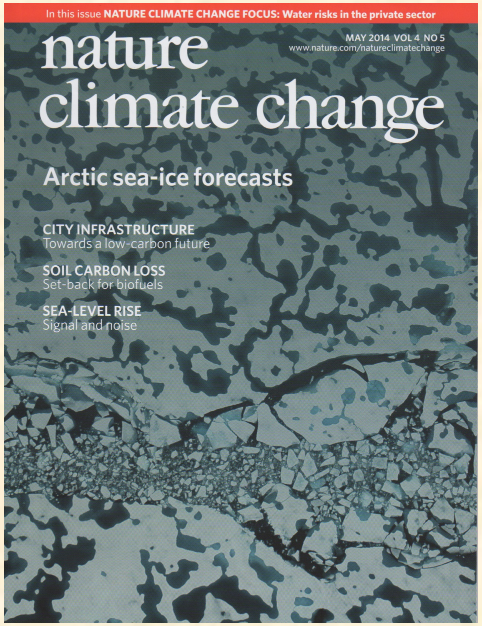
We found a strong, negative correlation between the **modelled** early melt season integrated pond fraction and the **observed** September sea ice extent minima.

This is a correlation between **anomalies**, e.g. an unusually high pond coverage is correlated with an unusually low ice extent.

For the first time it is possible to make **skilful forecasts** of September sea ice minima more than 2 months in advance, using melt pond cover.

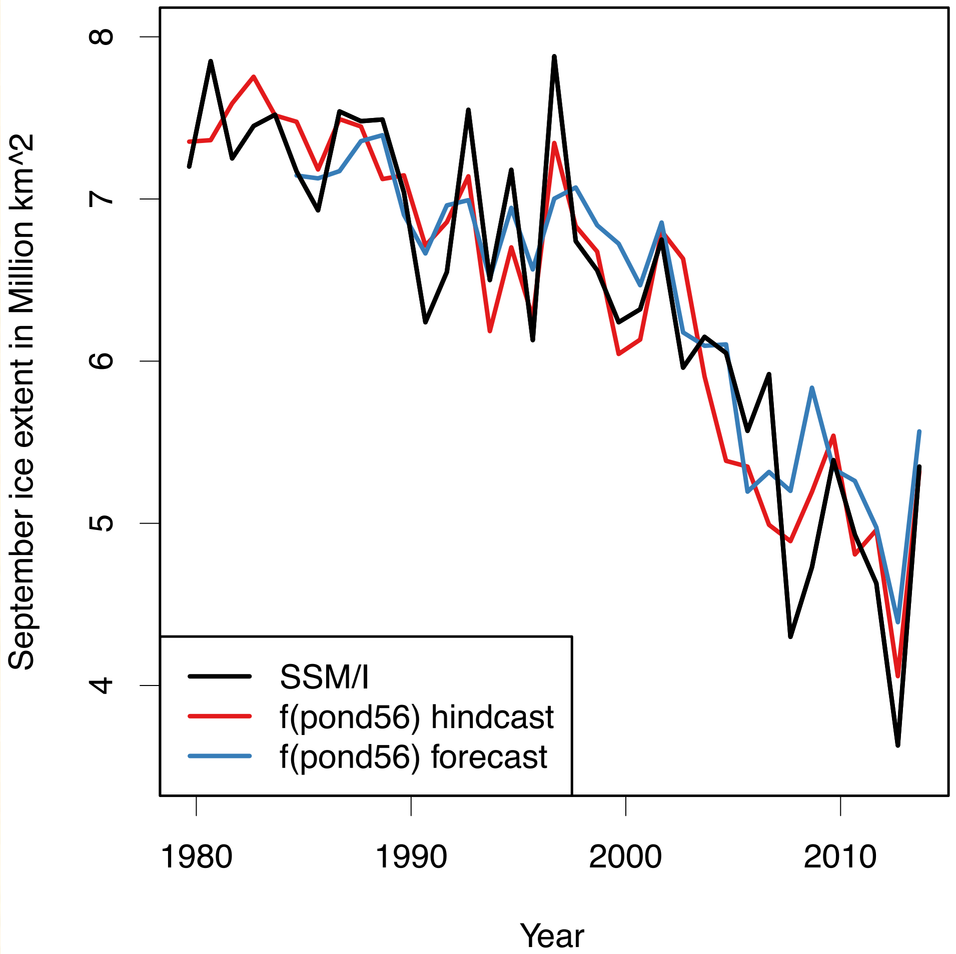


Maximum skill in late June but noteworthy skill in late May.



Schroeder, Feltham, Flocco, and Tsamados [2014]

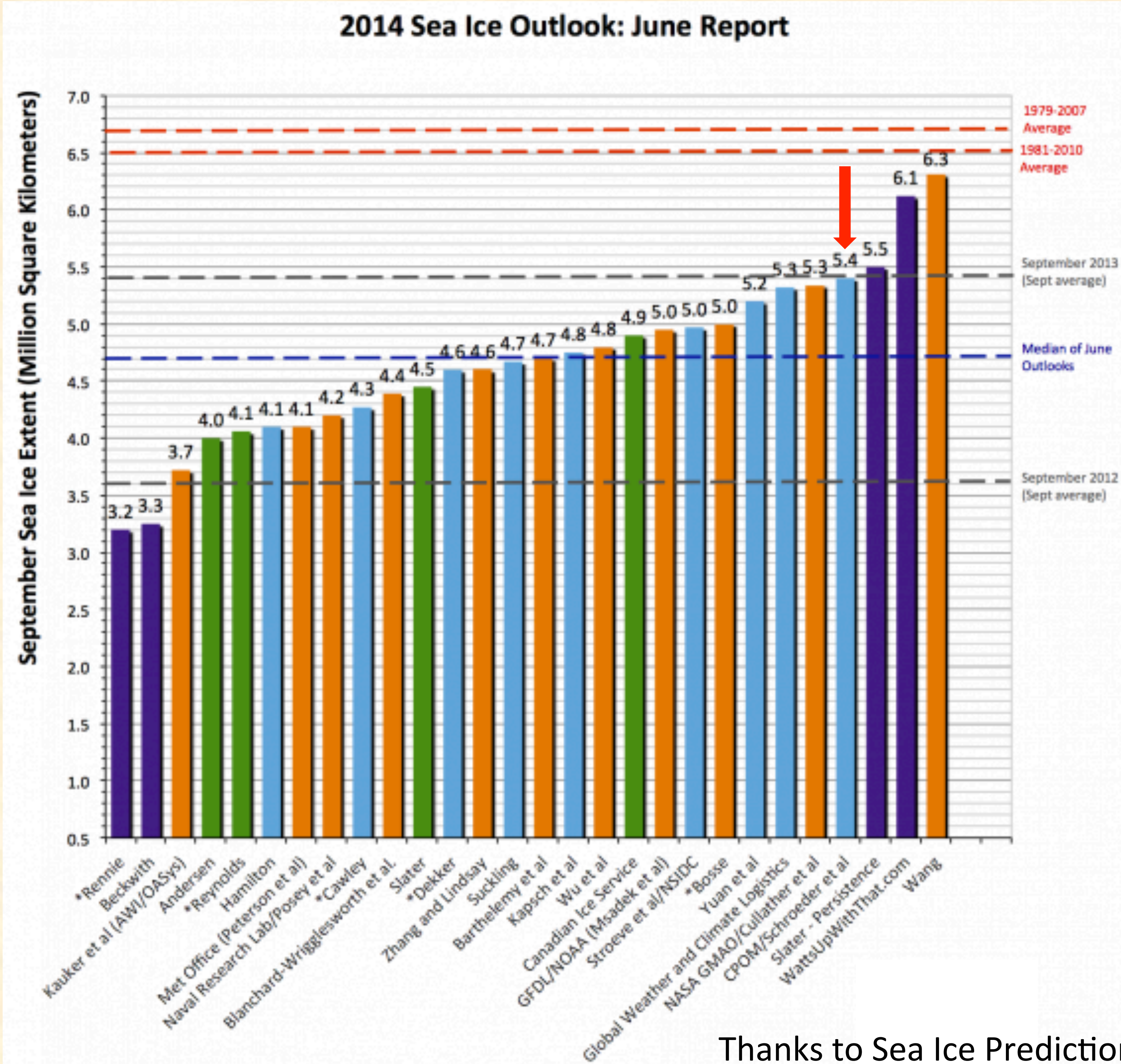
Our melt pond technique made the **most accurate** prediction of sea ice minima for September 2013



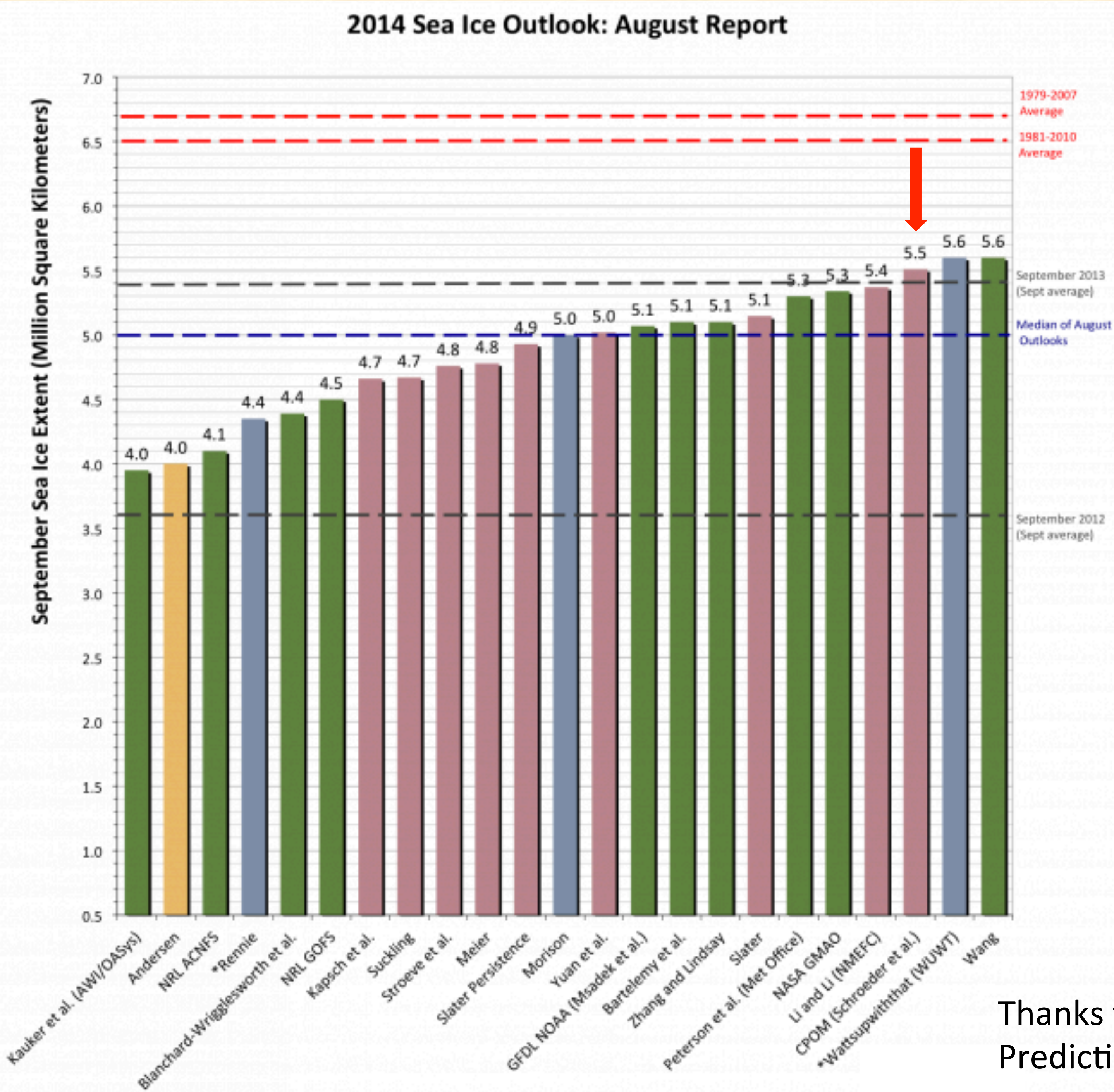
2013 forecast:
5.6 +/- 0.4
Million km^2

SSMI:
5.4
Million km^2

We believe the success of using melt ponds to predict ice extent is due to it incorporating two important factors: the thin ice fraction (upon which ponds collect) and the integrated surface melt.



Thanks to Sea Ice Prediction Network

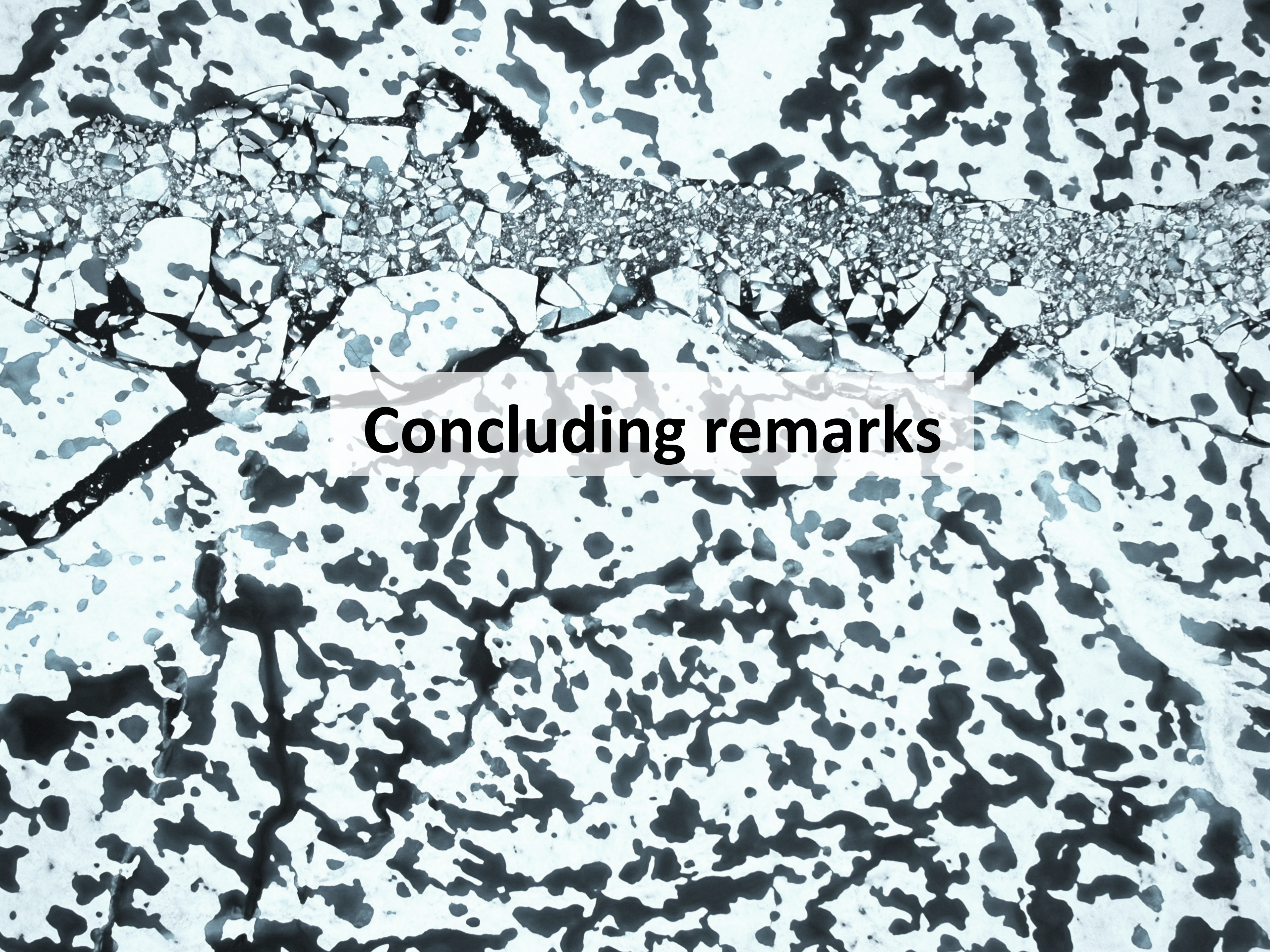


Thanks to Sea Ice Prediction Network

Summary remarks

- A physically realistic melt pond model has been incorporated into a climate sea ice model.
- Strong correlation between pond fraction in spring and September sea ice (R=-0.80 for de-trended time-series), physically explained by the albedo feedback mechanism.
- We can forecast September ice extent with an error of about 0.44 M km^2 and a skill value of S = 0.41.
- On 16 June, we predicted the 2014 sea ice minimum to be 5.4 M km^2 +/- 0.5 M km^2.
- Including physically-realistic melt ponds promises to improve GCMs for seasonal sea ice forecasts and climate predictions.

Concluding remarks



Take home message

- Accurate simulation of atmospheric and oceanic conditions play a large role in accurate prediction of sea ice

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- ... but we should not underestimate the importance of realistic sea ice physics in models.

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- It is shown that more realistic physics has a leading order impact on sea ice simulations…

Take home message

- Accurate simulation of atmospheric and oceanic conditions play a large role in accurate prediction of sea ice

- ... but we should not underestimate the importance of realistic sea ice physics in models.

- It is shown that more realistic physics has a leading order impact on sea ice simulations…

- ... and improves the predictive ability of models.

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

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.