Sea ice modelling for climate applications

Helene Banks

Ann Keen, Jeff Ridley, Jonathan Gregory, Alison McLaren

Met Office

William Connolley (BAS)

Martin Vancoppenolle (UCL)

Bill Lipscomb (Los Alamos)

7th September 2006

Outline

1. Introduction
2. Horizontal representation
3. Dynamics
4. Thermodynamics
5. Model design
6. Results from IPCC models
7. Conclusions

1. Introduction

Aims

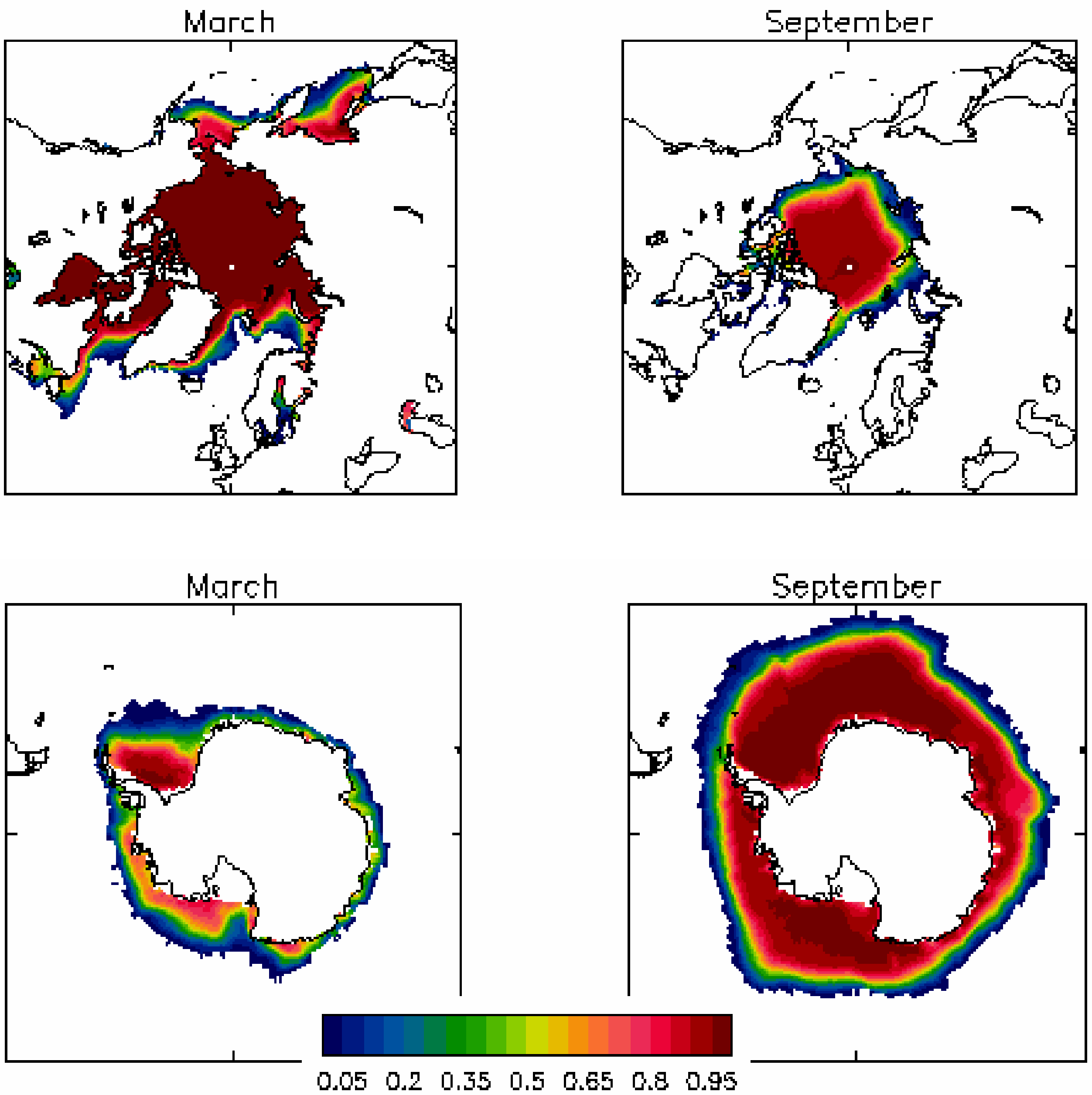
- What do models need for a good representation of climate?

- What is state of the art in sea ice modelling for climate?

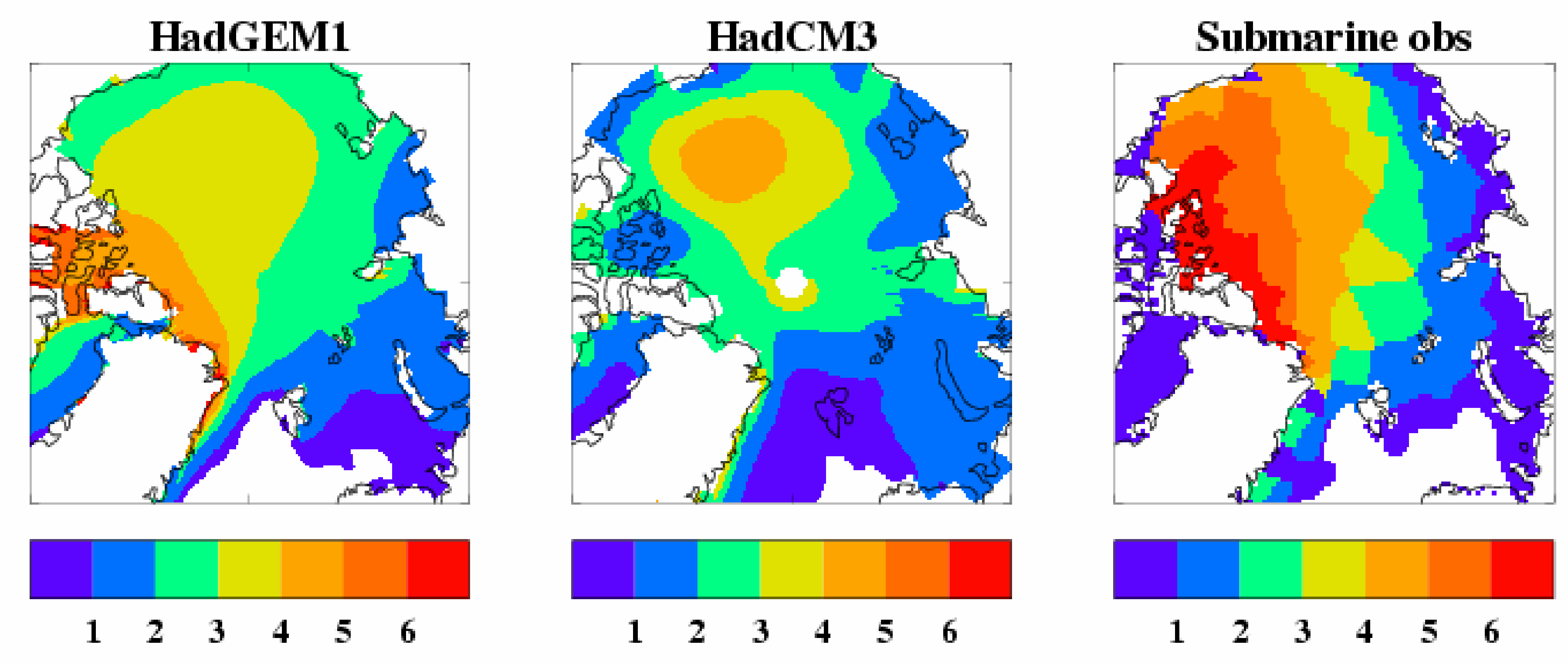
Background on sea ice

- On average sea ice covers 1/20 of the area of the global ocean
- Maximum and minimum sea ice occur in Northern (southern) hemisphere in March and September (vice-versa)
- Arctic ice area ranges from 5-13 x10^6 km^2
- Antarctic ice area ranges from 3-16 x10^6 km^2

HadISST ice concentration: 1979-2002



Winter ice thickness (m)



- 17 sub cruises (1960-1982)
- HadGEM1 mean = 2.6m, sub mean = 2.9m (north of 65°N)

Links to atmosphere and ocean

- Sea ice has an interface with atmosphere and ocean
- Sea ice growth and melt is determined by the surface heat and freshwater fluxes and ocean surface temperatures
- Sea ice motion is driven by windstresses and ocean currents

Why is sea ice important to climate?

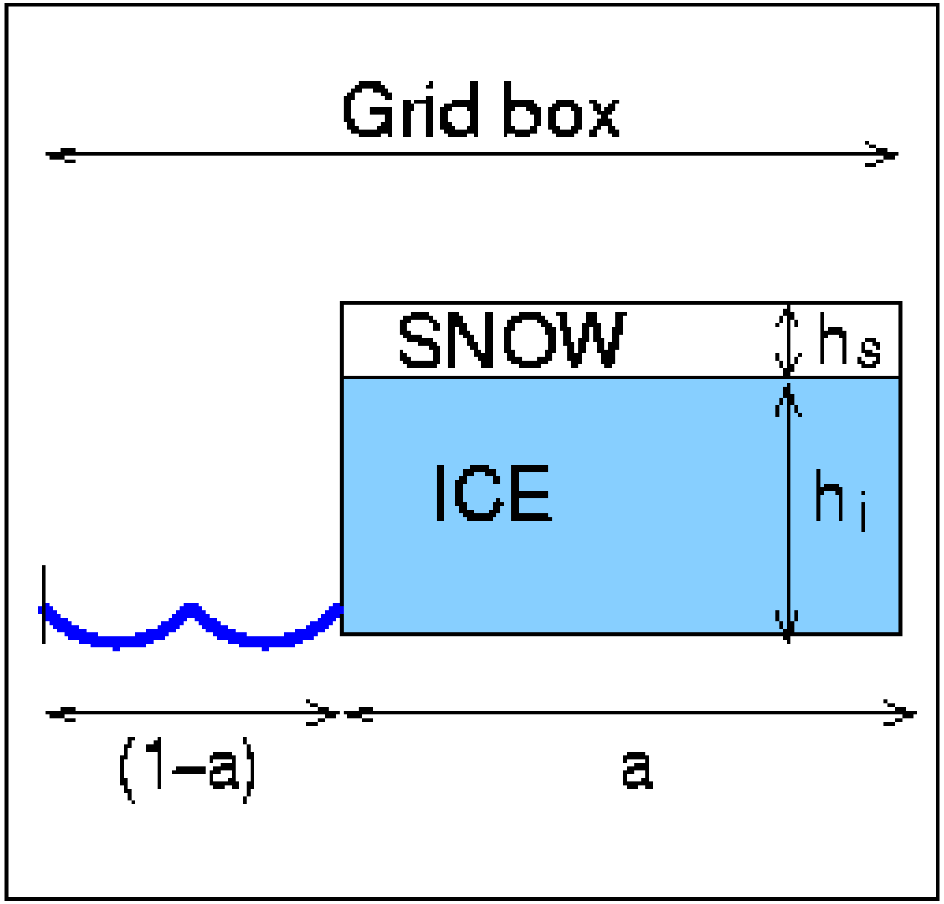
- Albedo:
  - High surface albedo reflects radiation back to the atmosphere. If sea ice begins to melt, lowering albedo will warm the ocean and lead to faster ice melt.
- Insulation:
  - Presence of sea ice insulates the ocean from losing heat and cools surface air temperature.
- Ocean salinity:
  - Brine rejection when ice forms, surface freshening when ice melts. Ocean salinity in high latitudes modifies water mass formation and strength of thermohaline circulation

What does a climate model need to represent?

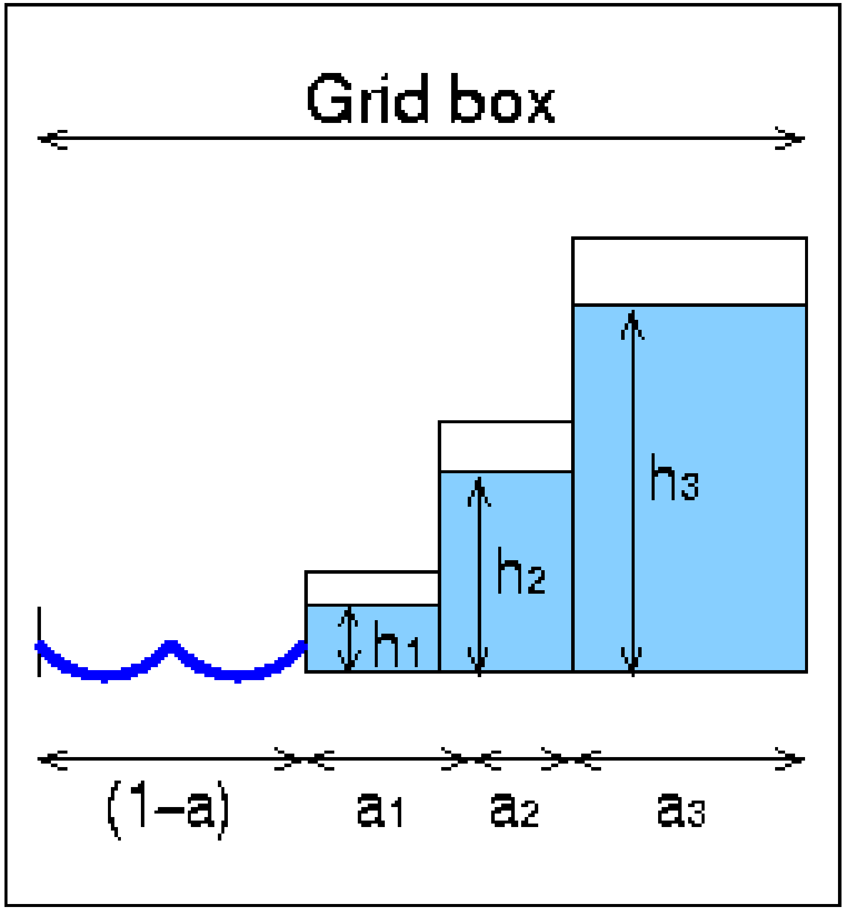
- Assume that for climate change simulations a good representation of present day sea ice is necessary (mean state and variability)
- Ice extents are important for albedo and insulation
- Surface properties (snow/ice/meltponds) are important for albedo
- Ice thicknesses (especially thin ice) are important for albedo, insulation and brine rejection

2. Horizontal representation

Horizontal representation

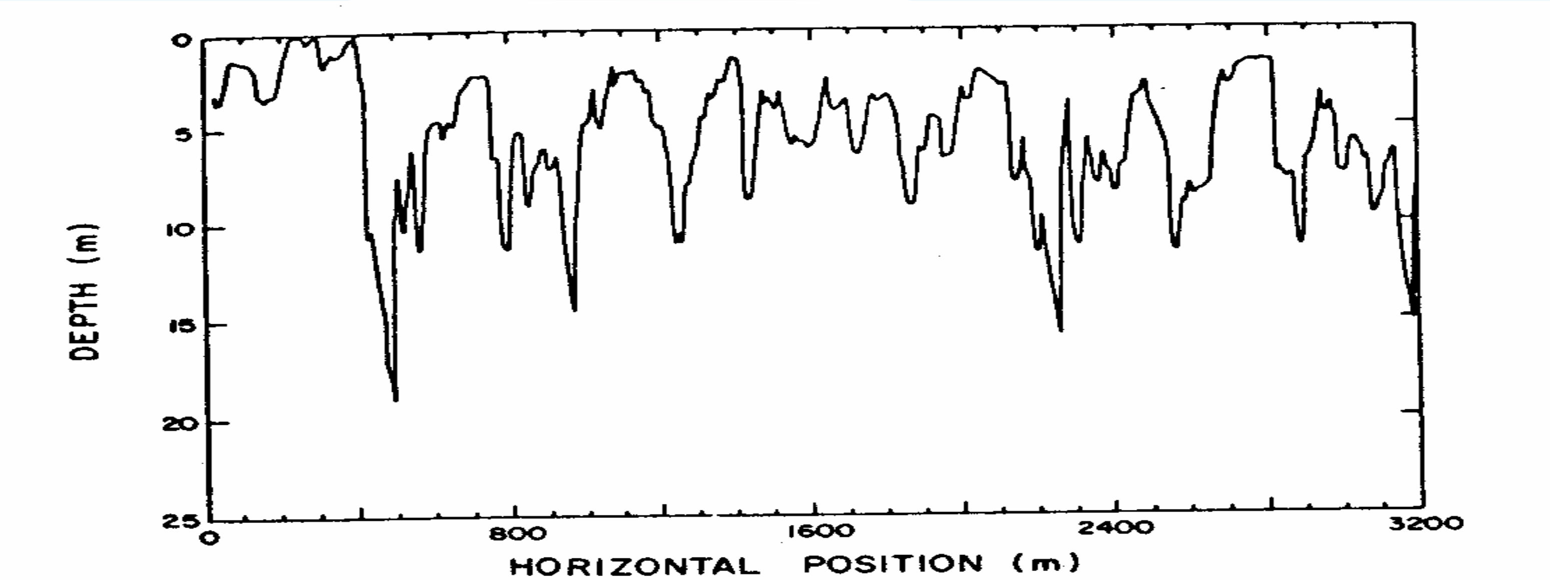


Simple



Sub-gridscale ice thickness distribution

Ice Thickness Distribution (ITD)

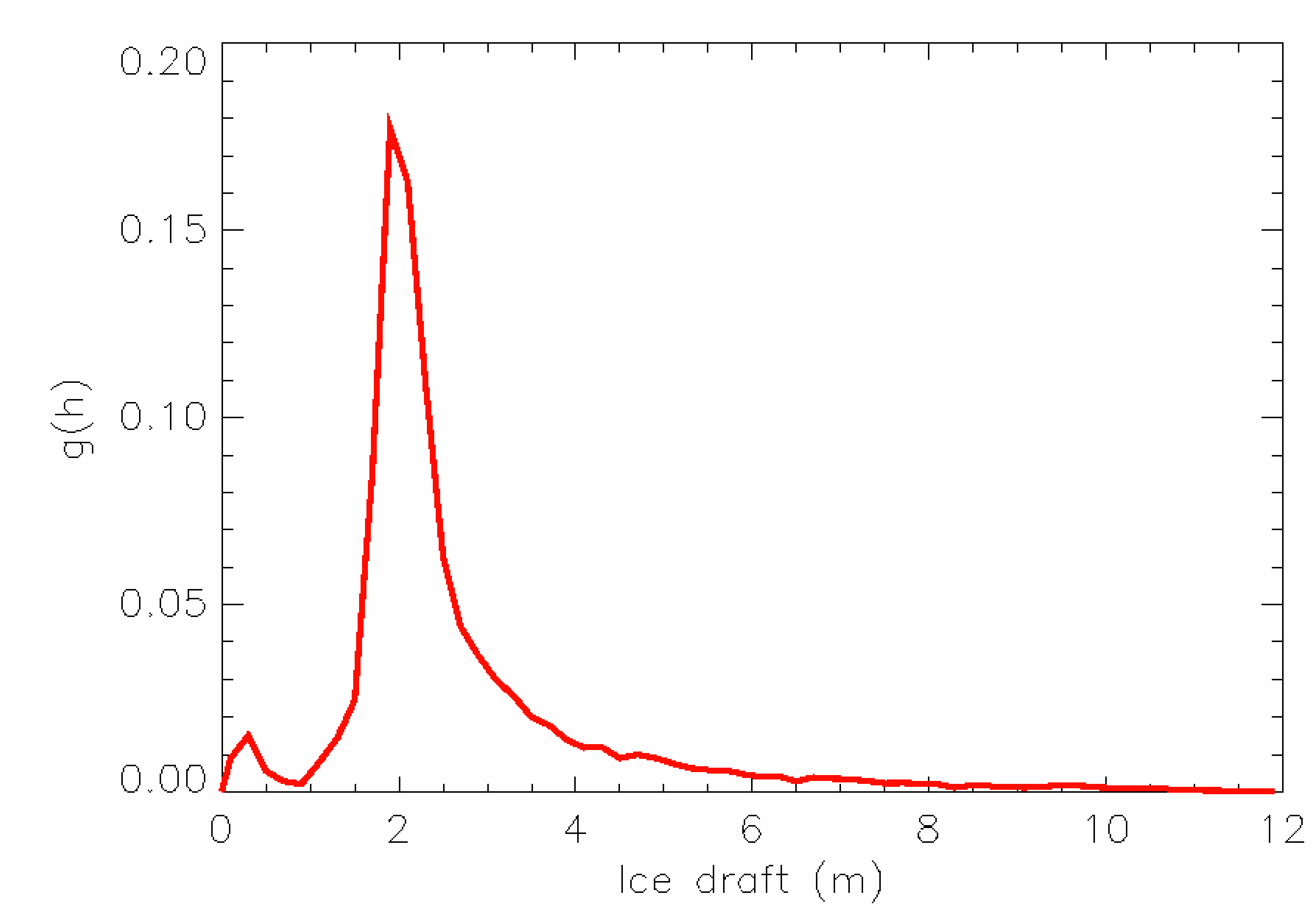


Swithinbank, 1972

- Ice thickness within ice pack is variable
- Many sea ice properties are very dependent on its thickness e.g. growth rate, compressive strength
- Properties of ice pack are especially sensitive to amount of thin ice

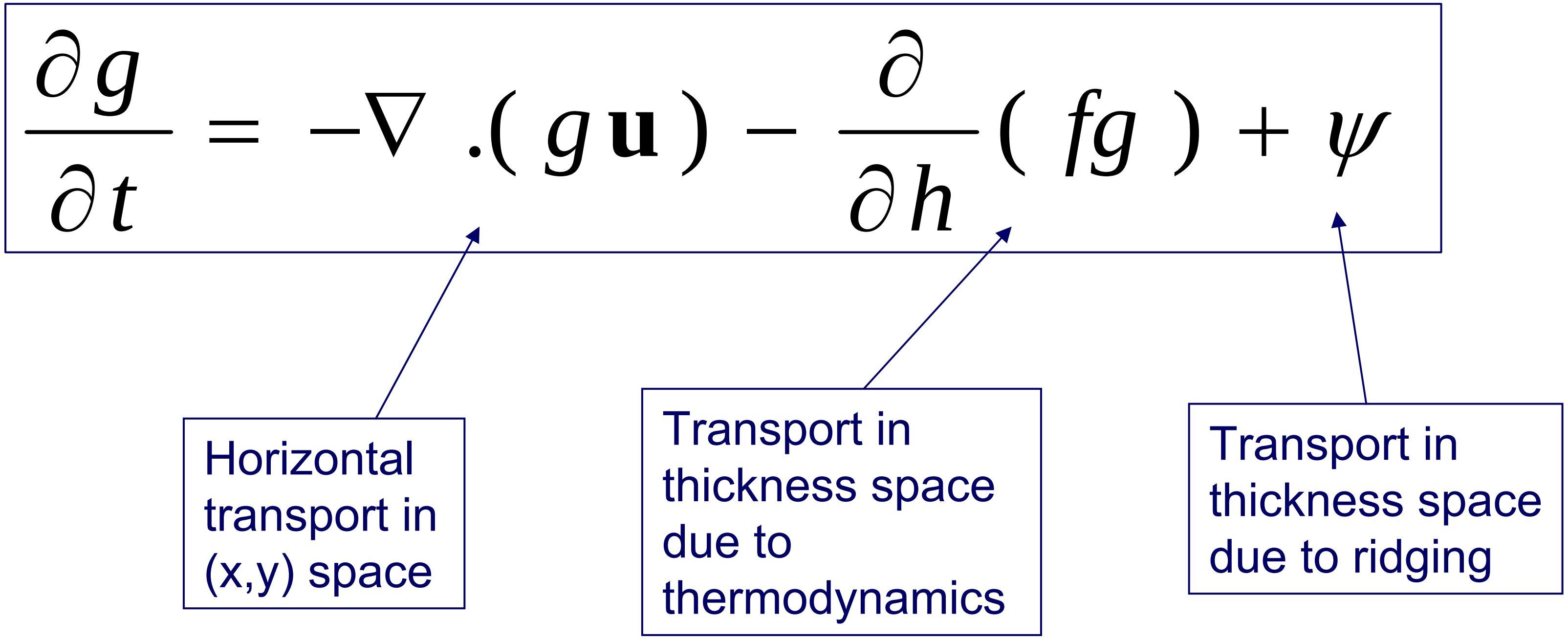
Observed Ice Thickness Distribution (ITD)

Submarine track, central Arctic, Sept 92, 50km



ITD scheme

g(x,h,t)dh is area covered by ice in range (h,h+dh)



$$\frac{\partial g}{\partial t} = -\nabla .(g\mathbf{u}) - \frac{\partial}{\partial h}(fg) + \psi$$

Horizontal transport in (x,y) space

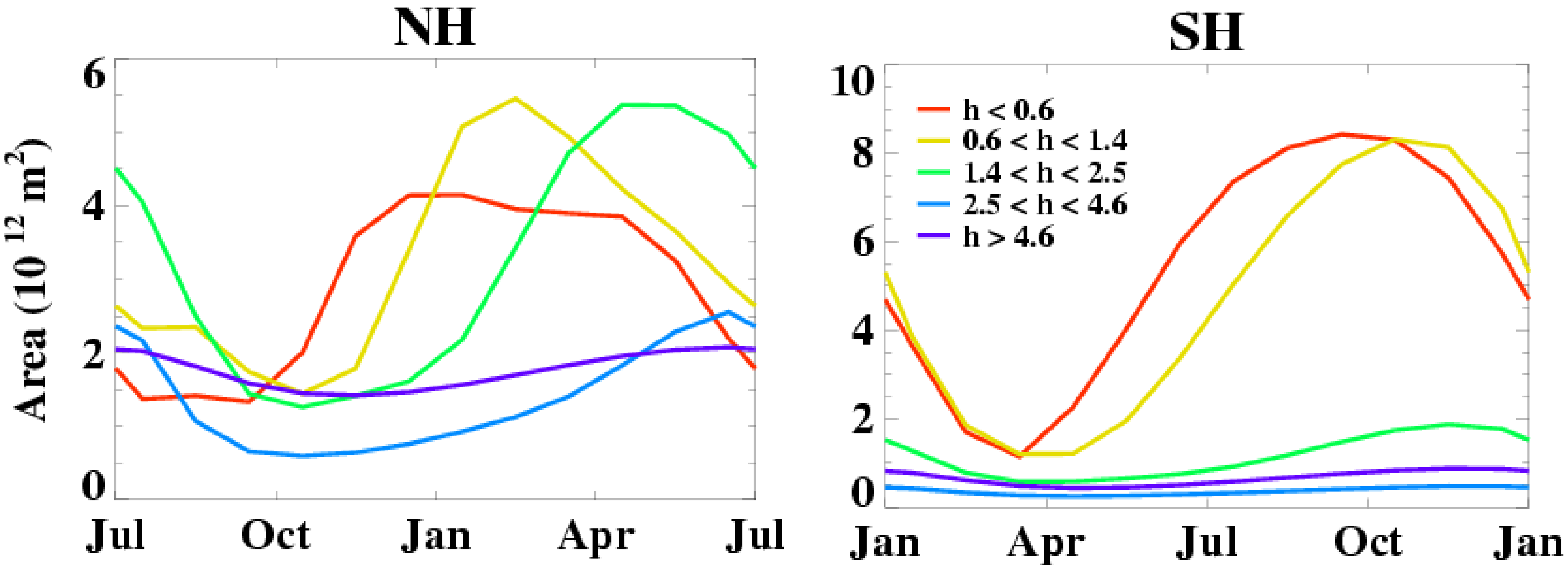
Transport in thickness space due to thermodynamics

Transport in thickness space due to ridging

How many thickness categories?

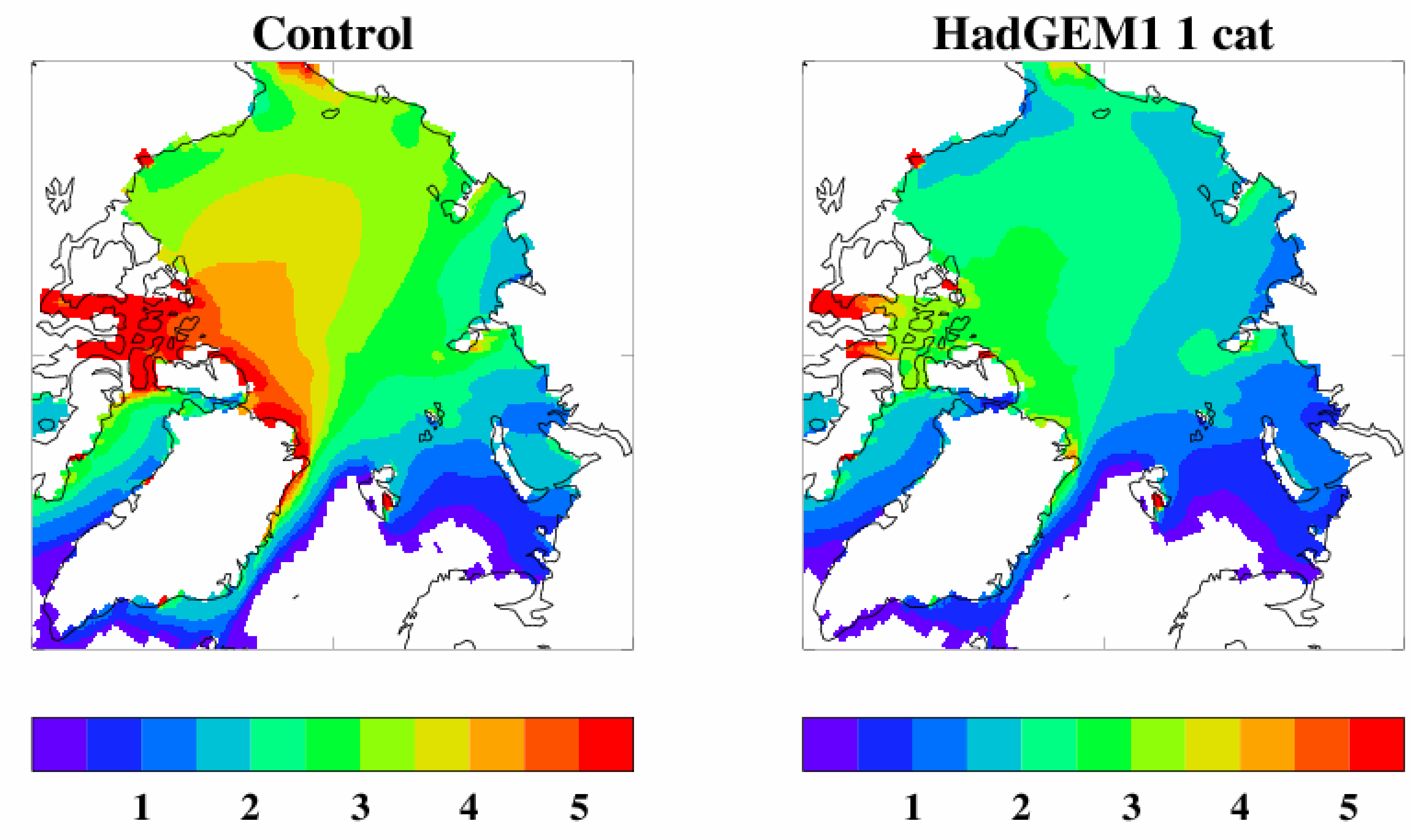
Bitz et al. conclude that 5 thickness categories are sufficient as long as the thin ice is adequately represented

Ice categories seasonal cycle

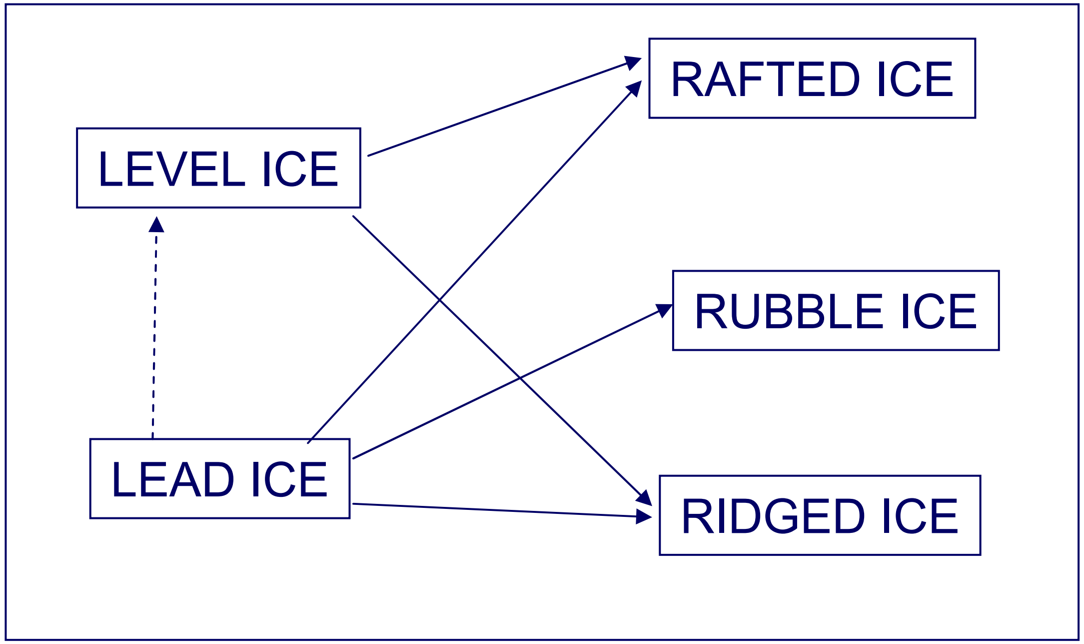


- Thinnest category grows first in autumn
- Volume transferred as ice grows
- Small seasonal cycle for thickest categories

March ice thickness (m): impact of resolving sub- gridscale ITD



Ice types



RAFTED ICE

LEVEL ICE

RUBBLE ICE

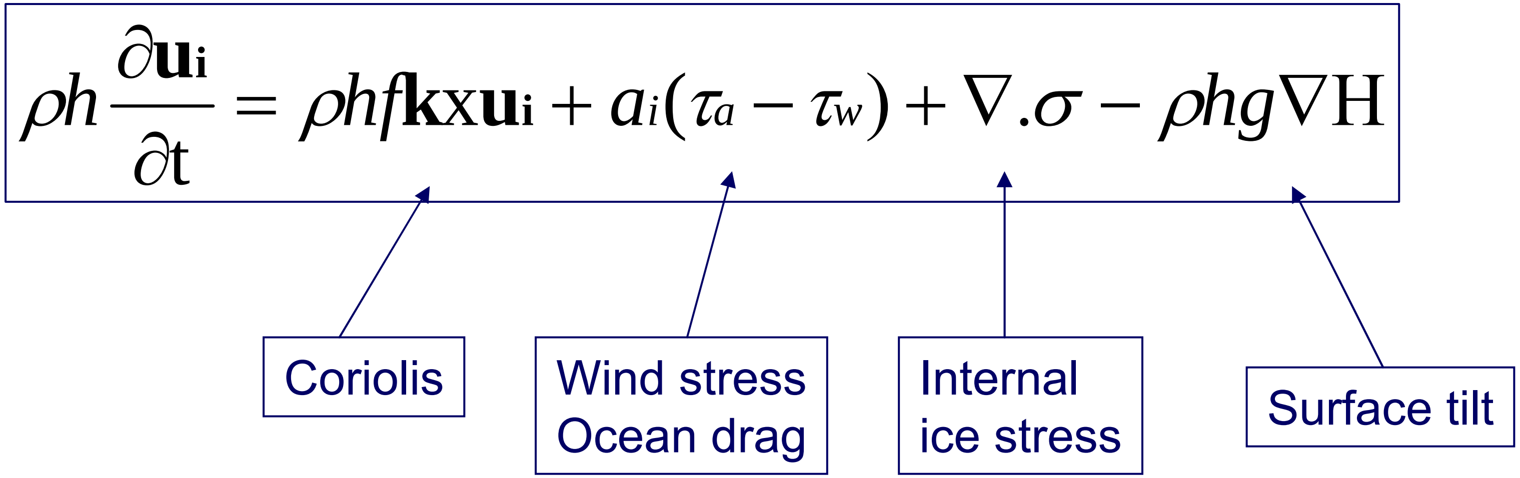
LEAD ICE

RIDGED ICE

Haapala, 2000

3. Dynamics

Dynamical balance



$$\rho h \frac{\partial \mathbf{u_i}}{\partial \mathrm{t}} = \rho h f \mathbf{k} \mathrm{x} \mathbf{u_i} + a_i(\tau_a - \tau_w) + \nabla.\sigma - \rho h g \nabla \mathrm{H}$$

Coriolis

Wind stress
Ocean drag

Internal
ice stress

Surface tilt

Freedrift

$$\boxed{0 = \rho h f \mathbf{k} \times \mathbf{u}_{\mathbf{i}} + a_i(\tau_a - \tau_w) - \rho h g \nabla \mathrm{H}}$$

- Acceleration is negligible on timescales of a few days. If ice rheology is also assumed to be unimportant, this is known as freedrift.

- Freedrift is a reasonable approximation for Antarctic sea ice

Thin ice approximation

- In thin ice (h is small):

$$\boxed{\tau_a \cong \tau_w \Rightarrow \rho_a C_a u_a^{\,2} = \rho_w C_w u_i^{\,2}}$$

- This implies:

$$\boxed{u_i \cong 0.02 u_a}$$

Rheologies: representing internal stresses

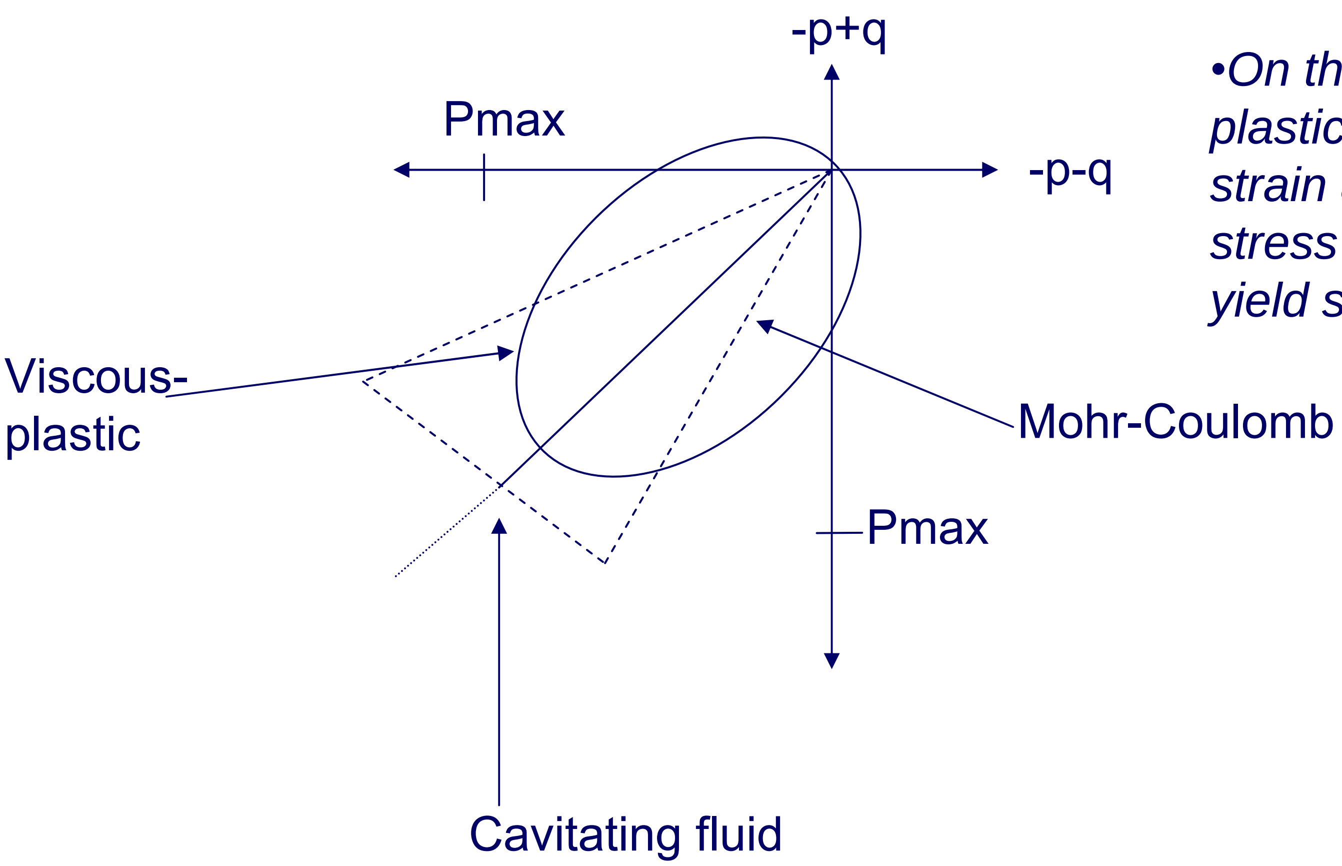
- The ice rheology is the parameterisation of the internal ice stress term
- Ice is generally assumed to diverge freely but resist compression
- The details of the relationship between stress and strain are defined by the rheology

Stress and strain definitions

- Stress: deforming force per unit area
- Compressive stress: normal to unit area
- Shear stress: tangential to unit area
- Strain: fractional extension of material

Rheologies

Yield curves in principle stress space



•Inside the surface, material is rigid

•On the surface, plastic flow occurs; strain adjusts so that stress is equal to yield stress

Description of rheologies

- Cavitating fluid: incompressible, pure shear behaviour. Convergence and divergence only at endpoints. No shear stress.

$$\boxed{\nabla.\sigma = -\nabla P}$$

- Viscous-plastic: plastic flow on yield curve. Inside ellipse, viscous behaviour allowed (strain rate proportional to stress)
- Elastic-viscous-plastic: elastic behaviour added (strain proportional to stress)
- Mohr-Coulomb: Includes shear stress

Calculating Pmax

- Pmax can be calculated from the Hibler (1979) parameterisation:

$$P_{\max} = p^{*} h e^{-K(1-a)}$$

- Alternatively, it can be related to the ITD and ridging according to Rothrock (1975)

Impact of rheologies

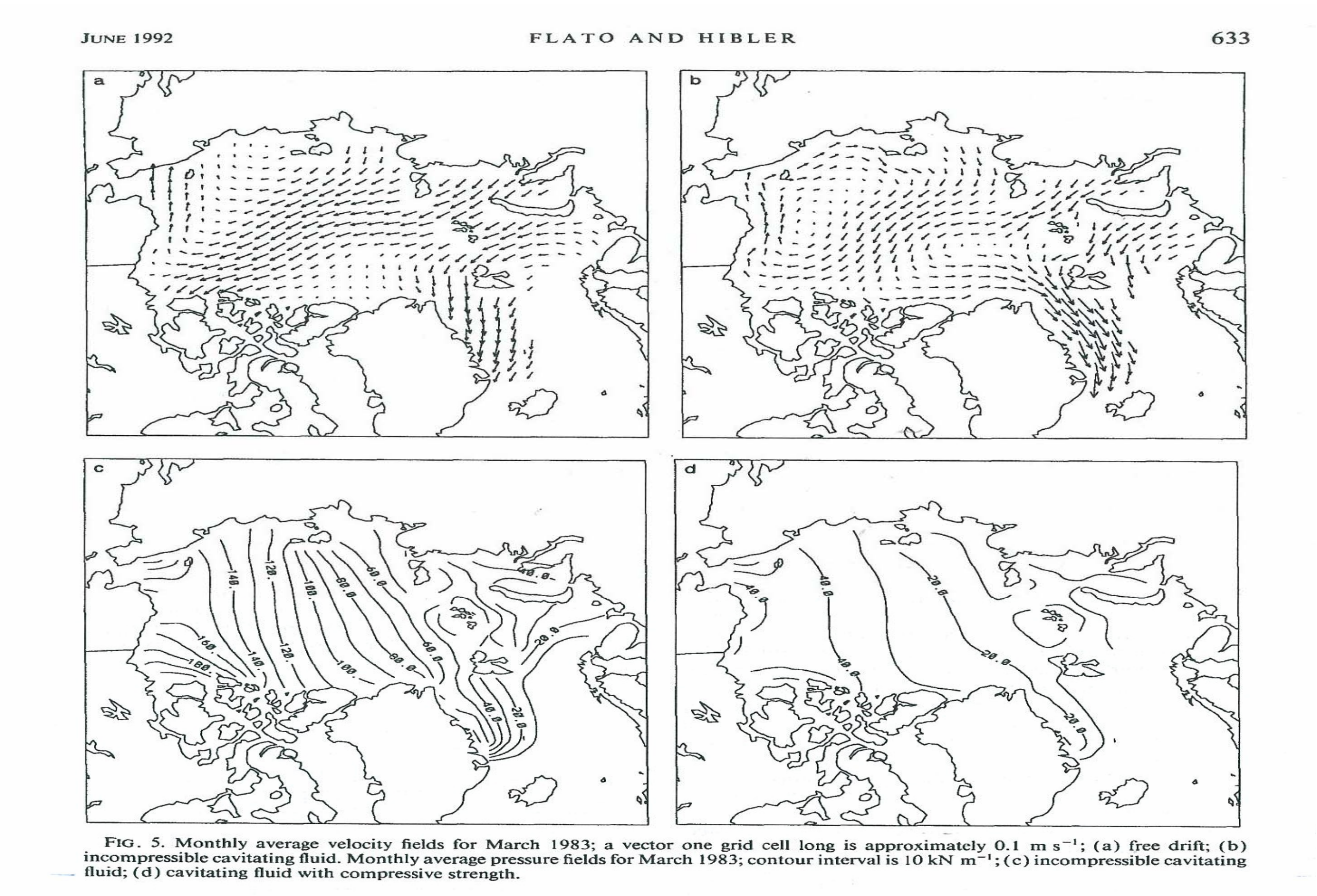


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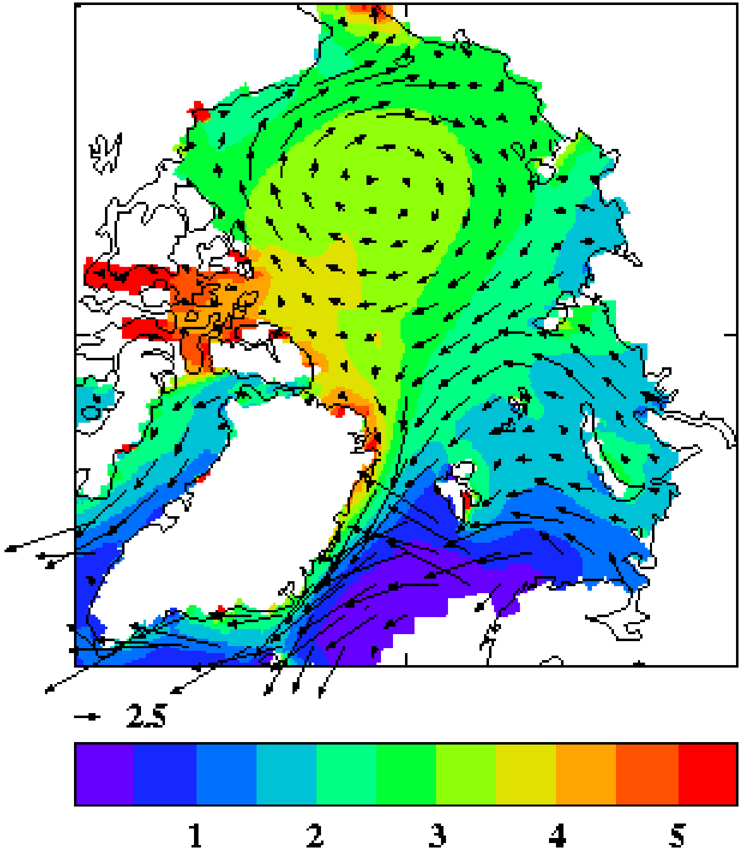
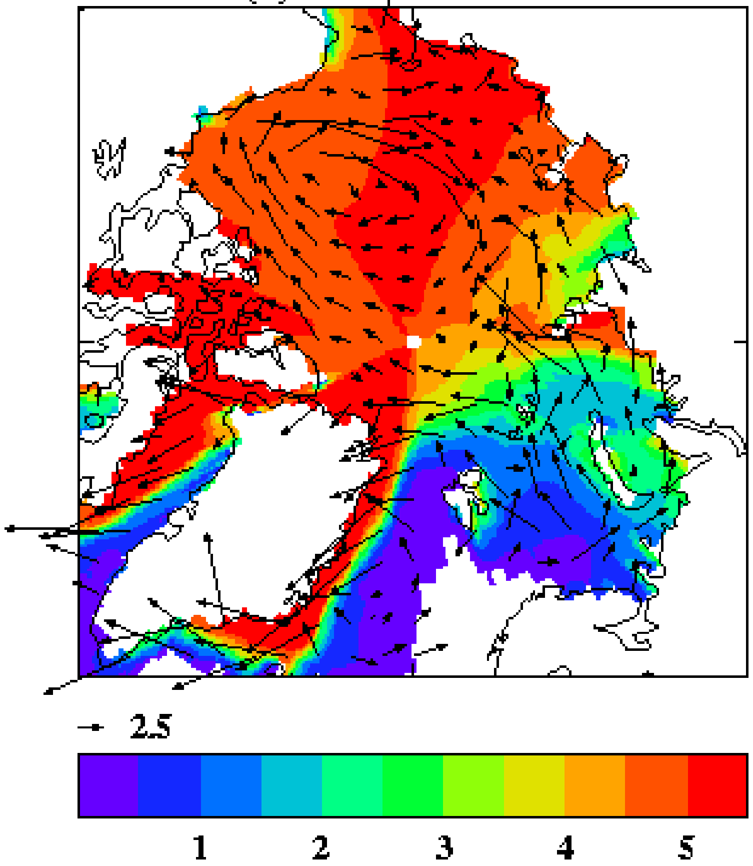
FIG. 5. Monthly average velocity fields for March 1983; a vector one grid cell long is approximately 0.1 m s^{-1}; (a) free drift; (b) incompressible cavitating fluid. Monthly average pressure fields for March 1983; contour interval is 10 kN m^{-1}; (c) incompressible cavitating fluid; (d) cavitating fluid with compressive strength.

March ice thickness (m): impact of EVP scheme

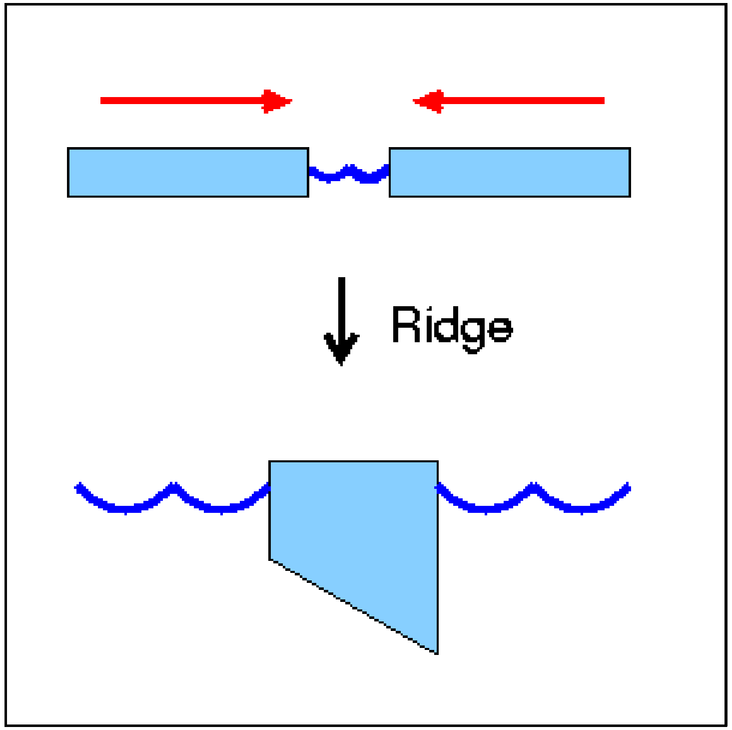
(a) HadCM3 T & EVP



(a) HadCM3 T&D



Ridging



- Convergence or shear
- Ice area reduced by thin ice -> thicker ice and open water

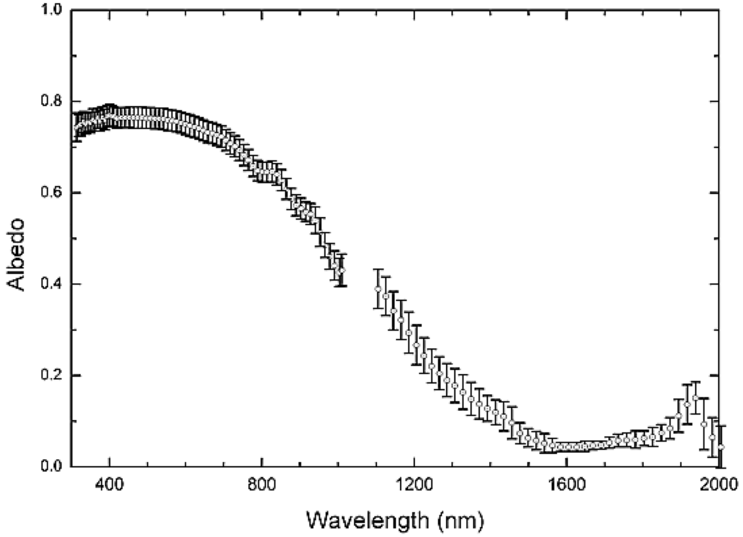
4. Thermodynamics

Thermodynamics

- Albedo
- Vertical representation
  - Multilayer thermodynamics
  - Brine pockets
- Interface fluxes
  - Surface
  - Basal

Sea ice albedo

The total albedo is defined as the ratio of the integrated outgoing short wave (250 - 2500 nm) radiation and the integrated incoming short wave radiation. The albedo of bare dry sea ice is greatest in the visible spectrum at 500 nm and least in the near IR.



The albedo of polar regions varies from that of open water (0.05) to that of new snow (0.90), and encompasses the entire range of albedos found on the surface of the planet. It is important in the representation of the ice albedo feedback in the climate system

Dependence on ice thickness

As ice thickens the formation of brine drainage channels and trapped brine inclusions result in increased internal scattering and higher albedo

0 - 5 cm	5 - 10 cm	10 - 15 cm	15 - 30 cm	30 - 100 cm
0.10	0.25	0.30	0.35	0.45

As the ice becomes stressed, ridged and rafted cracks form which increase albedo to 0.6 – 0.7.

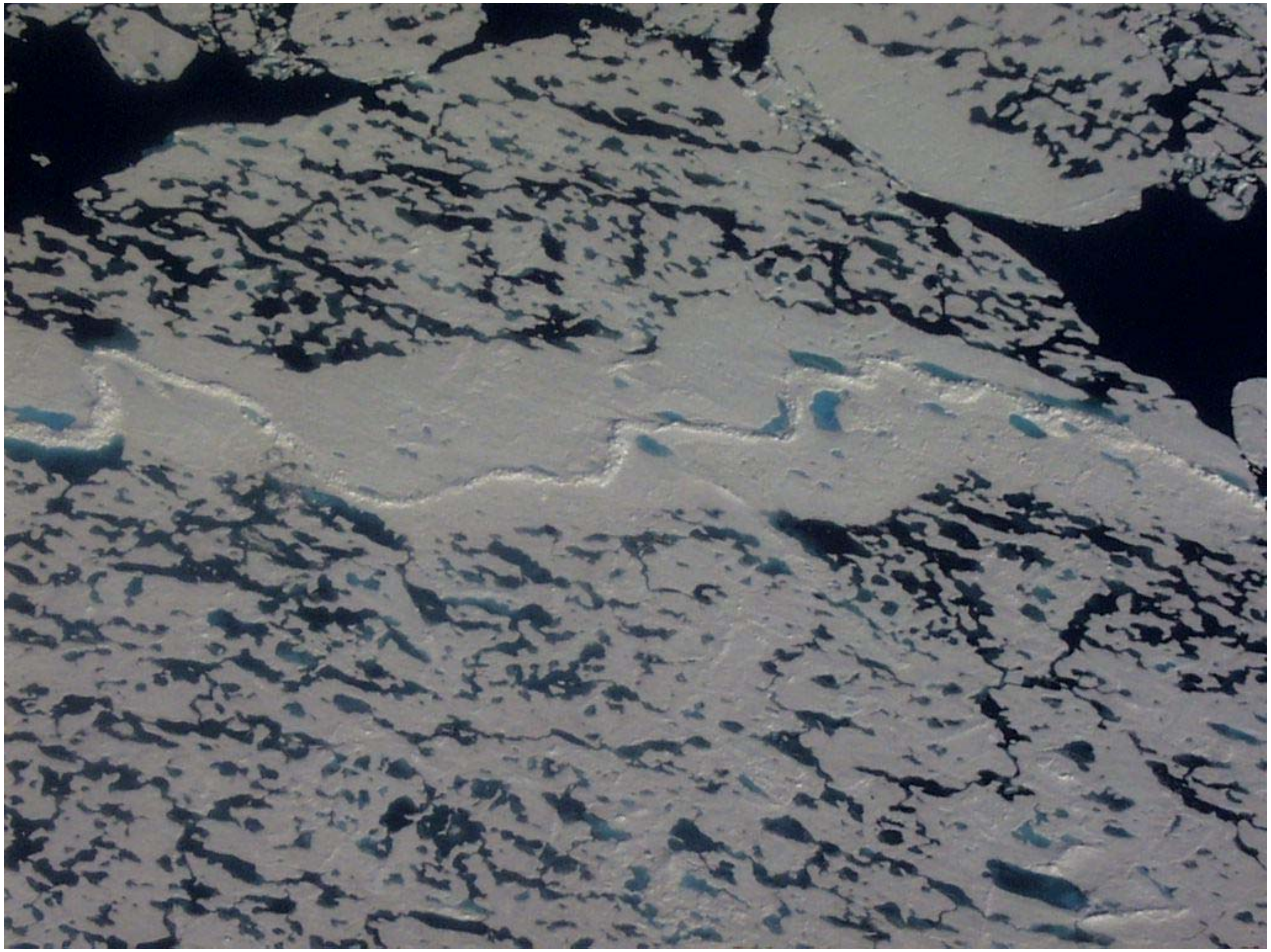
Dependence on snow cover characteristics

Fallen snow grain size and structure changes with temperature (Antarctic sea ice always snow covered). Rainfall and fresh snow fall can significantly alter albedo on short time scales.

dry fresh snow	dry windblown snow	wet snow
0.87	0.81	0.77

Effect on albedo of snow is logarithmically dependant on the snow depth, representing drifting and partial coverage of the ice.

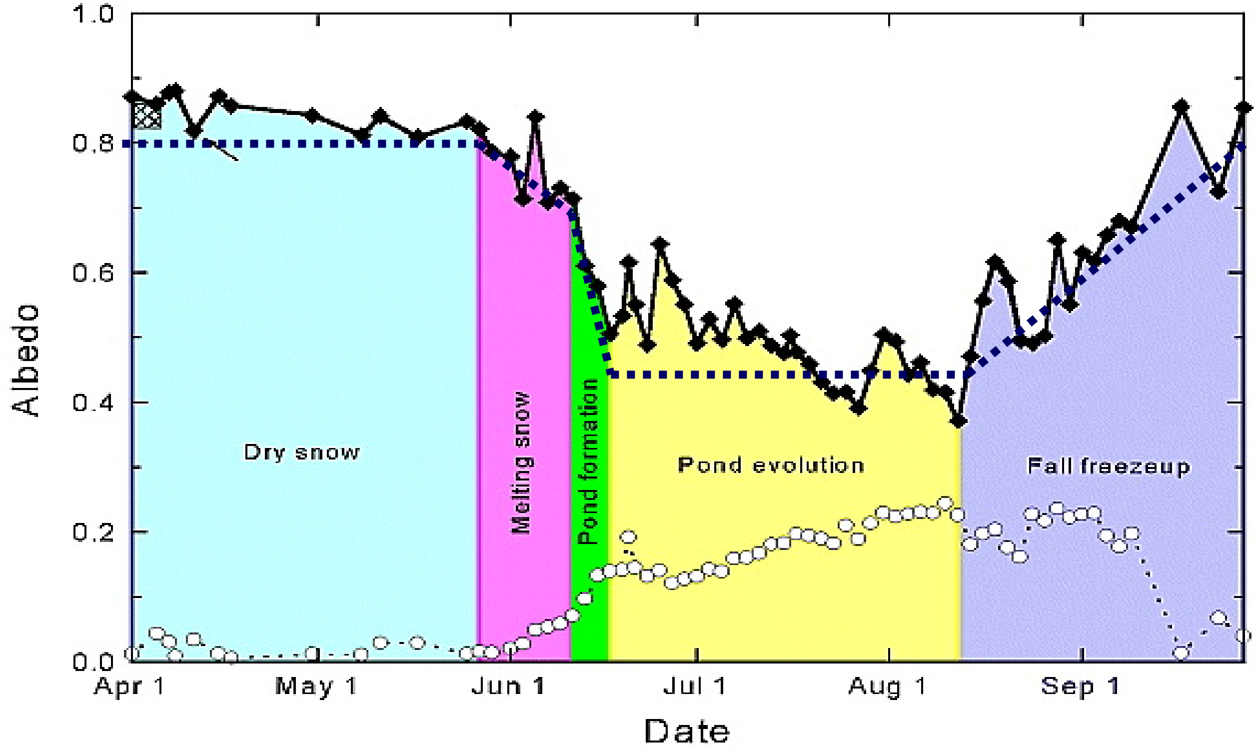
Meltponds



Meltponds

- Ponds develop during continued melting once ice is snow-free
- Ponds grow laterally and in depth draining through the brine channels as quickly as they melt.
- Albedo of the ponds is ~0.1-0.2 depending on depth and impurities (e.g. soot) which settle on the bottom of the pond.
- Ponds coverage of the ice surface grows to ~40% significantly reducing the structural strength of the ice.
- Ponds freeze-up in autumn, and, followed by fresh snowfall the albedo returns to the winter value.

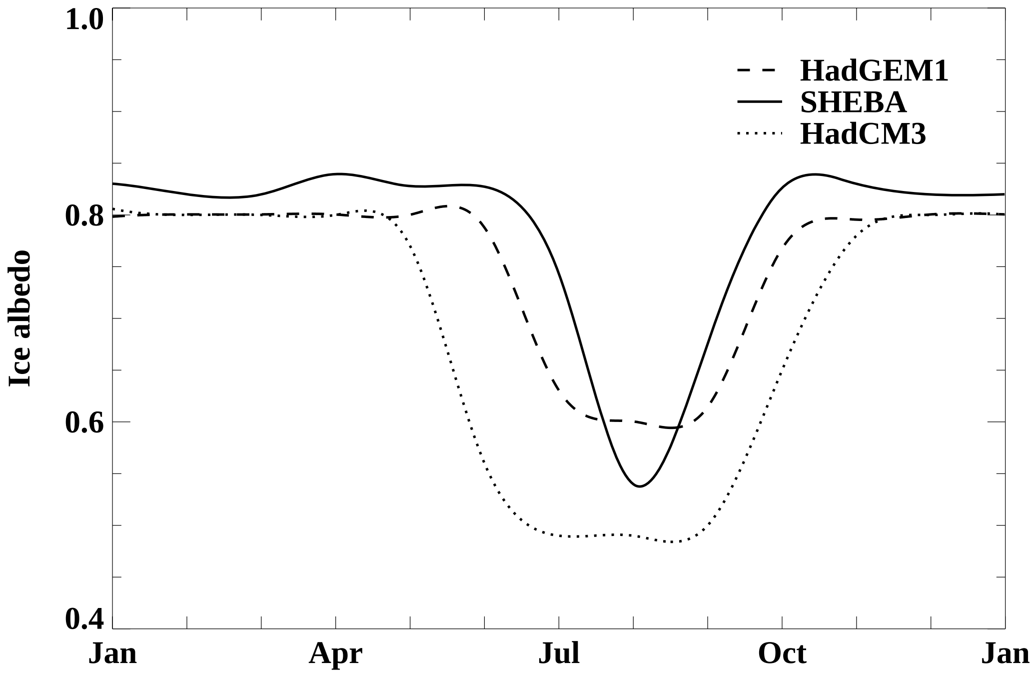
Annual cycle of albedo



Observations of mean albedo along a 100m line on multiyear ice at the SHEBA field site (from Perovich et al., 2002) throughout the summer season. Open symbols are the spatial standard deviation of albedo.

Models simulate the annual cycle by breaking the season into characteristic periods based on surface air temperature (dotted line).

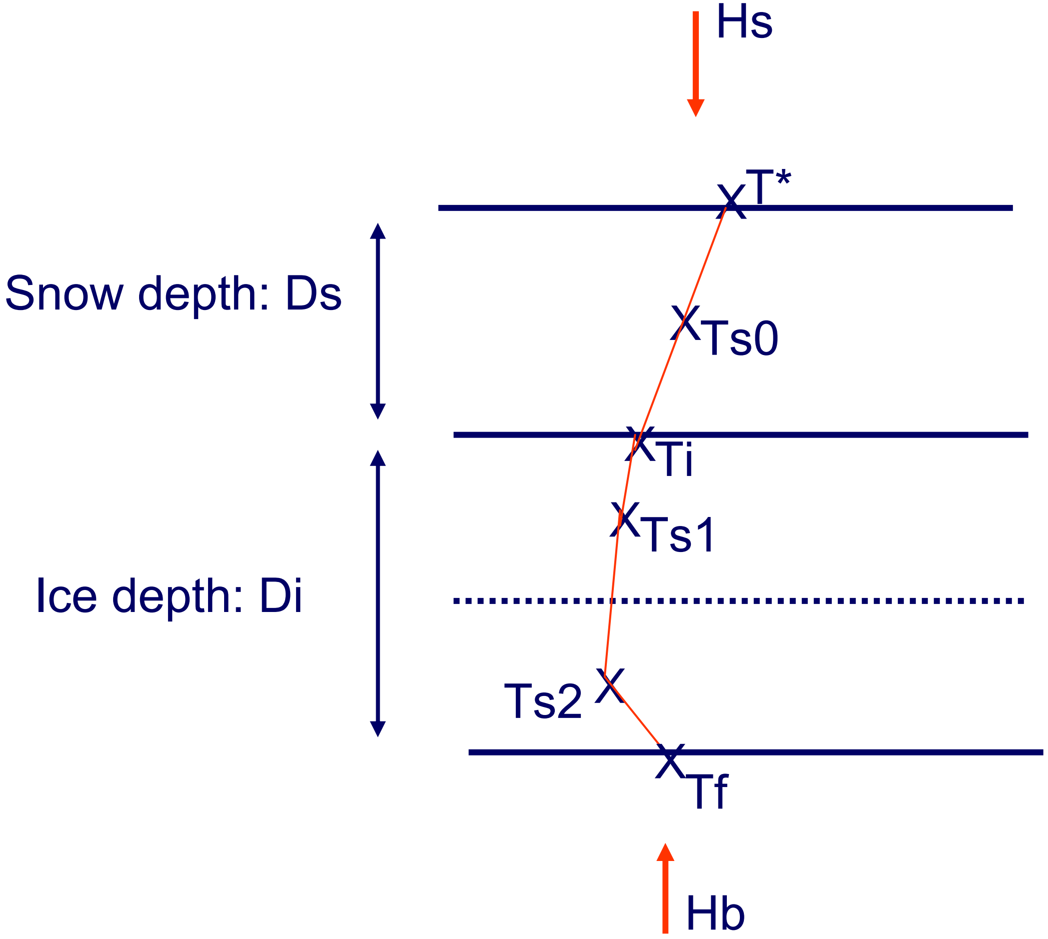
Annual cycle of albedo



The exact representation of a single season of point observations is not possible with a climate model. Indeed, different parameterisations, as a function of air temperatures, of the summer melt cycle in models can result in significantly different sea ice characteristics.

Too much summer melt can result in thinner winter Arctic ice cover and consequently increased heat fluxes to the atmosphere.

Vertical layers



Hs

T*

Snow depth: Ds

Ts0

Ti

Ts1

Ice depth: Di

Ts2

Tf

Hb

$$\boxed{\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2}}$$

Semtner (1976)

Brine pockets

- Radiation penetrating ice does not immediately melt ice but warms the interior and melts patches of high salinity ice
- Liquid trapped within ice is known as “brine pockets”
- Brine pockets are important because they store heat:
  - Brine pockets will refreeze with onset of cooling
  - Ice is thicker at start of autumn than if brine pockets were not present

Brine pockets

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + \kappa I_0 e^{-\kappa z}$$

Penetrating radiation stored and used to keep temperature from dropping below freezing point (Semtner 1976).

Equivalent to heat being released from refreezing of brine pockets.

Surface forcing

$$F_{net}(T_0) = F_r(1-\alpha) - I_0 + F_l - \sigma T_0^{\ 4} + F_s + F_e + k\frac{\partial T}{\partial z}$$

If Fnet(Tm) >0 then ablation occurs

Otherwise solve for surface temperature To by setting Fnet(To)=0

Basal fluxes

Basal fluxes are very difficult to measure.

Ocean-ice heat flux can be represented as a function of the temperature difference between ocean and ice and the ocean drag:

$$F_b = \rho c_p c_h u_* (T_{ml} - T_f)$$

$$u_* = \sqrt{\tau_w / \rho}$$

McPhee (1992)

Ocean-ice heat fluxes need special treatment in the marginal ice zone where ice is thin

Ablation/accretion

$$F(T) = q(S,T)\frac{dh}{dt}$$

where, the energy of melting, q, is given by:

$$q(S,T) = \rho c_0 (T_m - T) + \rho L_0 (1 + \frac{\mu S}{T})$$

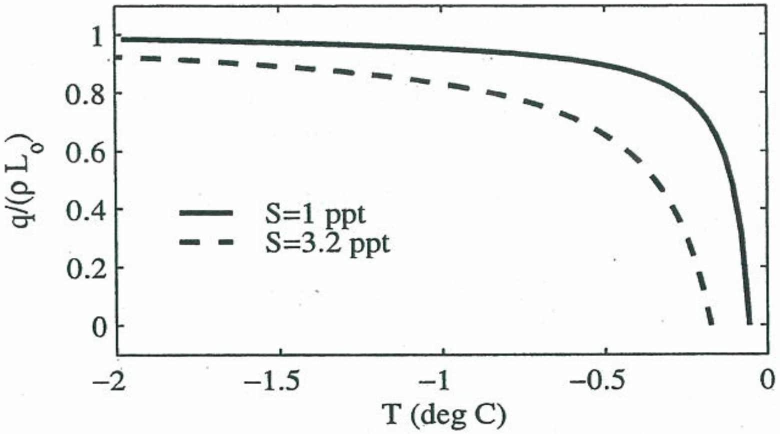


Figure 1. Energy of melting relative to the latent heat of fusion of pure ice as a function of temperature for $S = 3.2‰$ and $S = 1‰$.

White ice formation

- If snow is below freeboard, snow is converted to ice until the base of the snow is at freeboard
- This is known as white ice formation

Impact of increasing number of layers

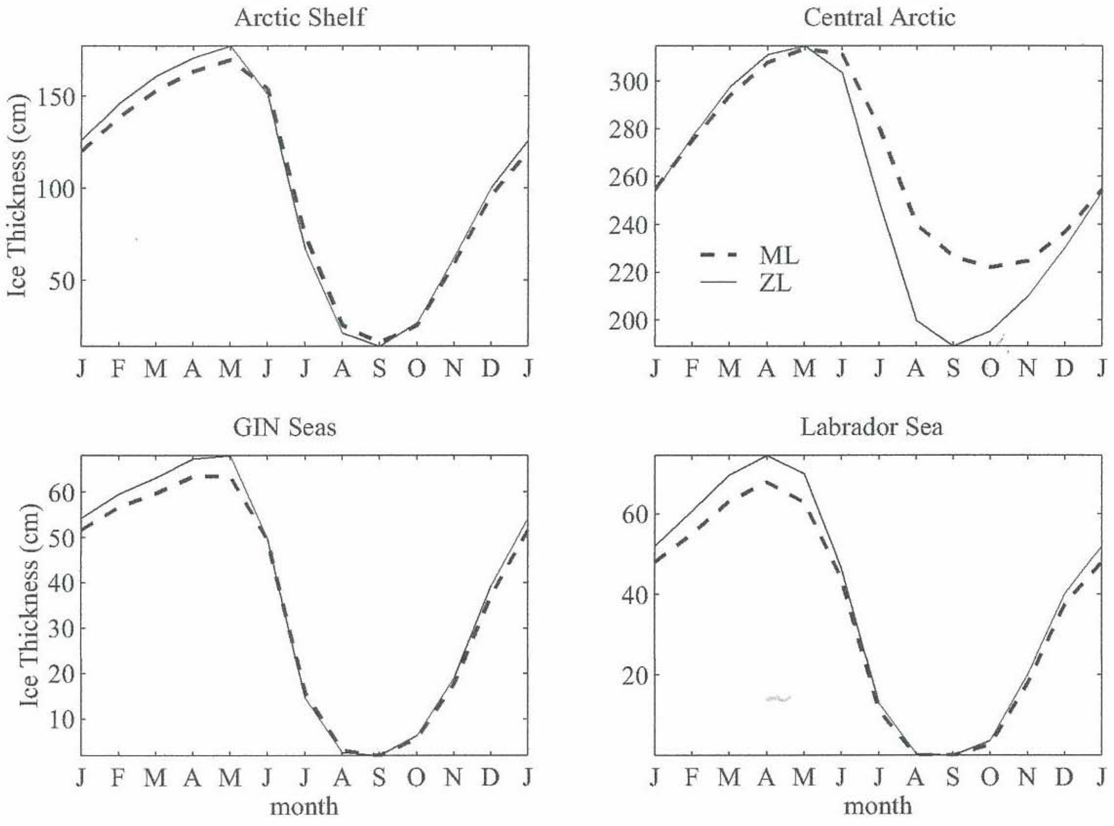
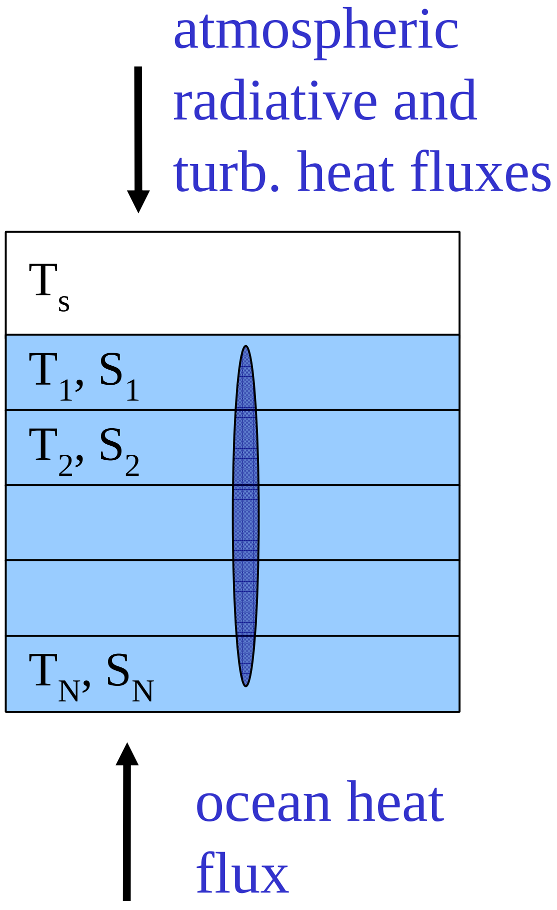


Figure 15. Mean annual cycle of ice thickness for cases with multi-layer (ML) and zero-layer (ZL) thermodynamics separated into subregions defined in Fig. 1.

Sophisticated salinity model (1D)

Multi-layer semi-empirical halo-thermodynamic model

- **thermodynamic** component (T) :
  Bitz and Lipscomb (1999), with T and S – dependent thermal properties
- **halodynamic** component (S) :
  - salinity computed in every layer
  - brine entrapment, gravity drainage, brine expulsion and flushing are resolved
- **coupling** through brine volume prescribed as a function of salinity and temperature
- **validated** with landfast sea ice data

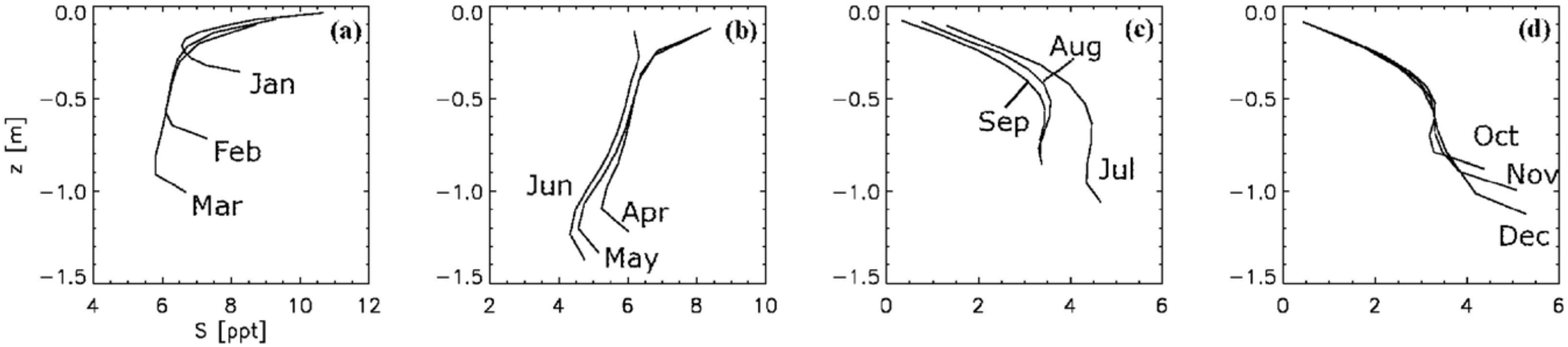


T : Temperature
S : Salinity

Vancoppenolle et al., 2006a

Sophisticated salinity model (1D)

Sea ice salinity profile for a year of model run under interpolated monthly climatological forcing.



The halodynamic model configuration affects ice growth and decay

Model configuration	annual mean ice thickness after 10 years
Interactive halo-dynamic component	2.85 m
Prescribed vertically-varying profile	2.53 m
Prescribed isosaline profile	2.29 m

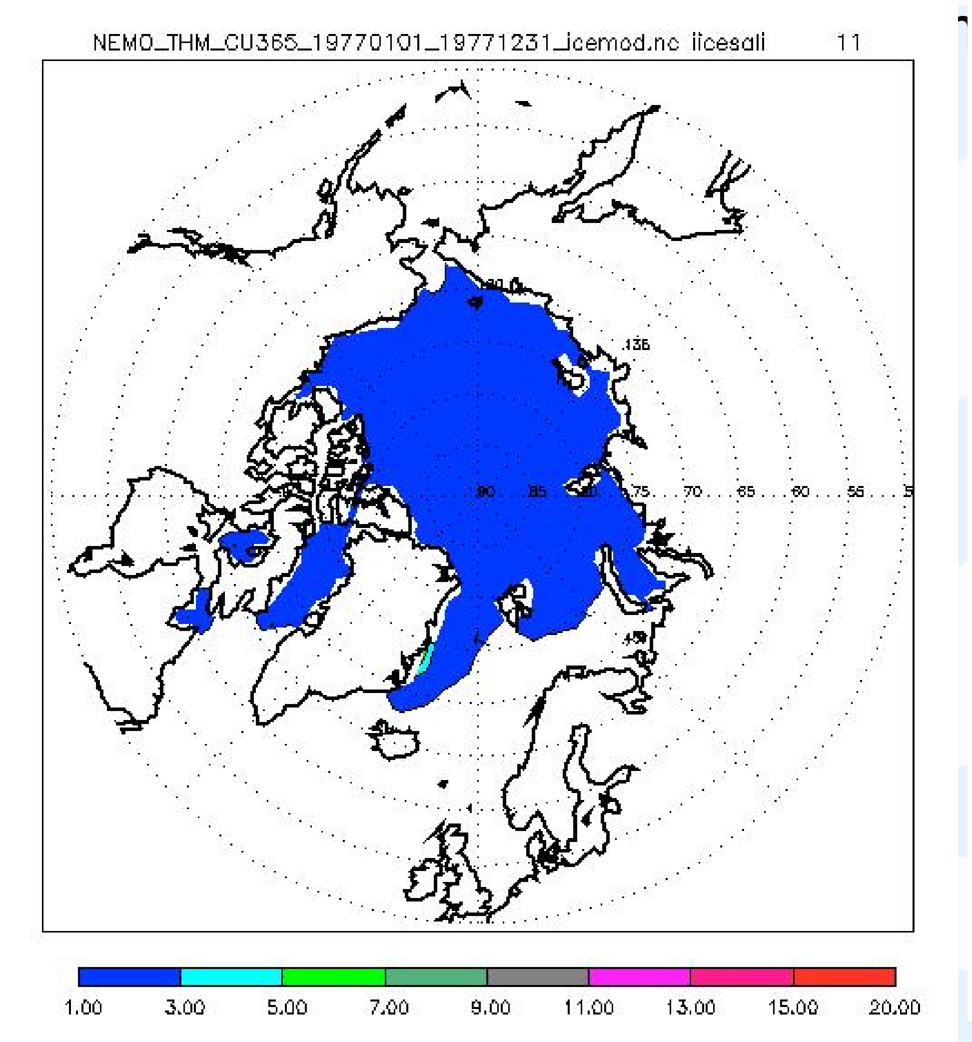
Vancoppenolle et al., 2006b

Simplified salinity model (3D)

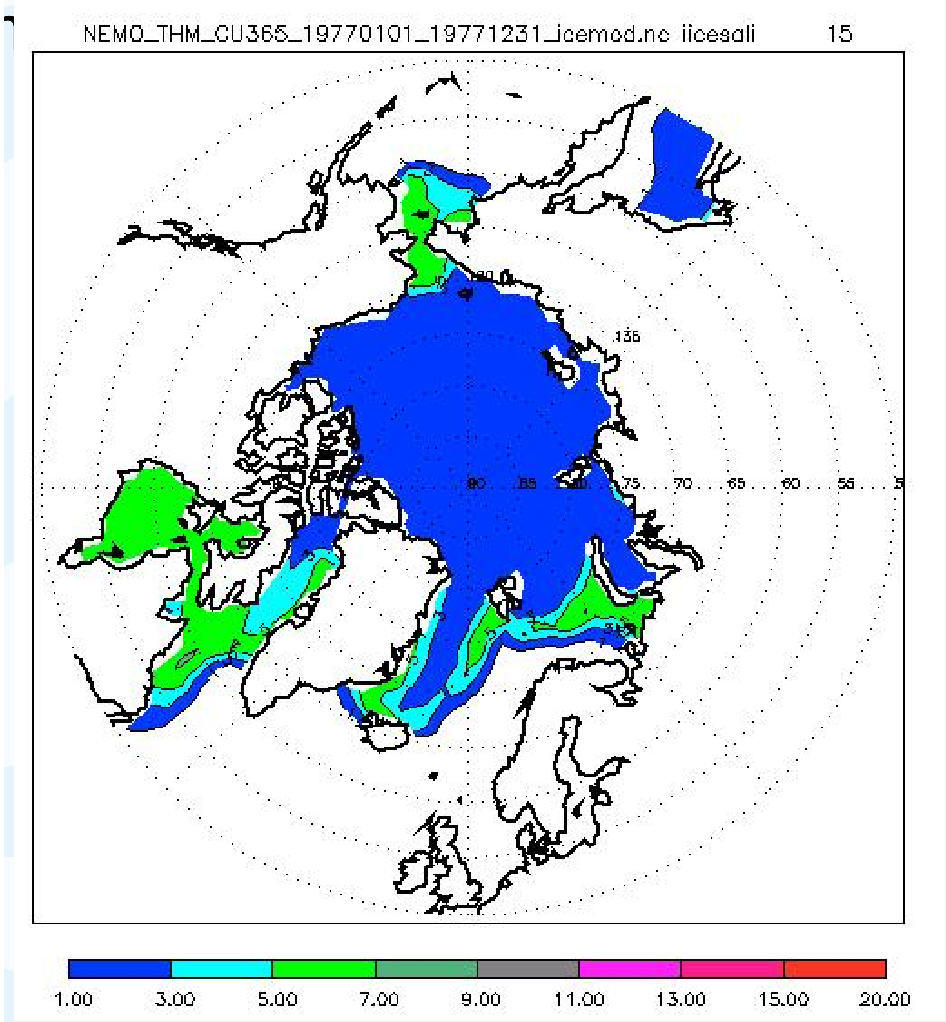
Empirical halo-thermodynamic model embedded into NEMO-LIM

- **halodynamic** component (S) :
  - only bulk salinity is computed
  - the profile (linear or isosaline) is prescribed in function of computed bulk salinity
    - vertically constant if S > 3.7 ppt (FY ice)
    - linear with S = O at the surface if S < 3.7 ppt (MY ice)
  - terms of tendency are parameterized as simplified functions of ice thickness, ice growth, surface temperature, ...
  - account for bottom accretion, lateral accretion, gravity drainage, flushing, snow-ice formation.
- the total mass of salt is advected
- the ice-ocean salt flux includes a brine drainage component
- **validated** with the more complex halo-thermodynamic sea ice model

Simplified salinity model (3D)

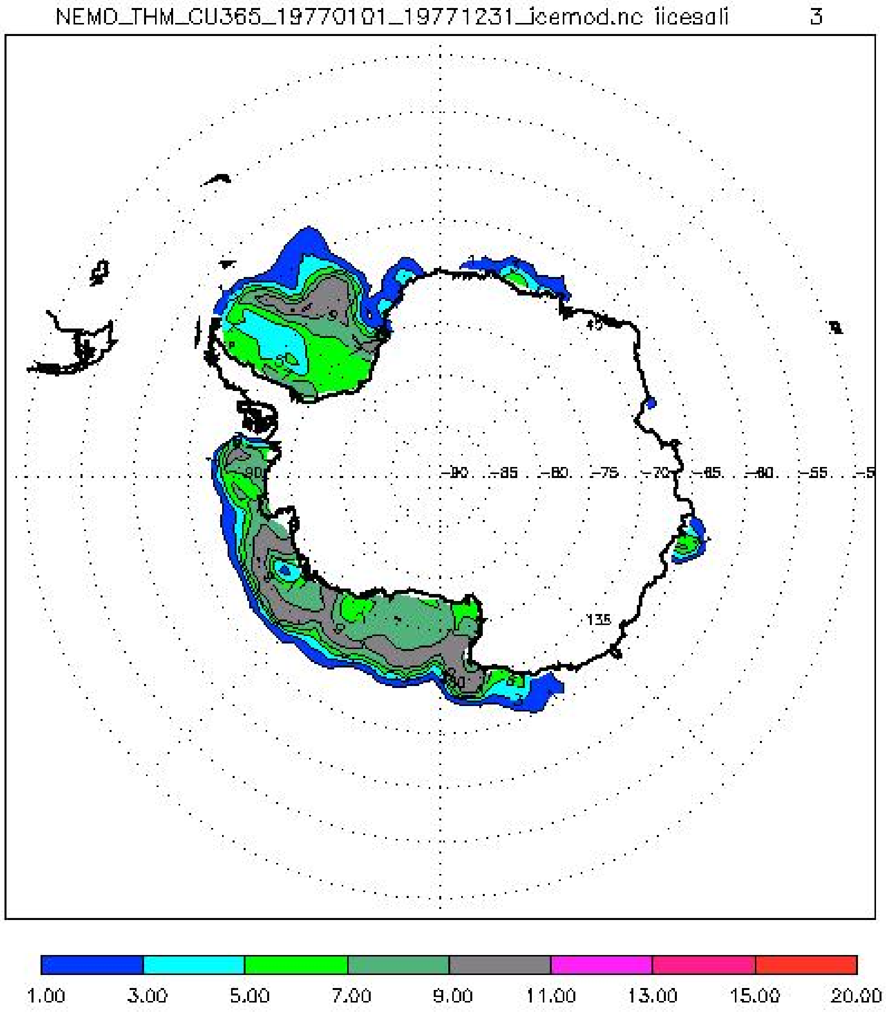


summer

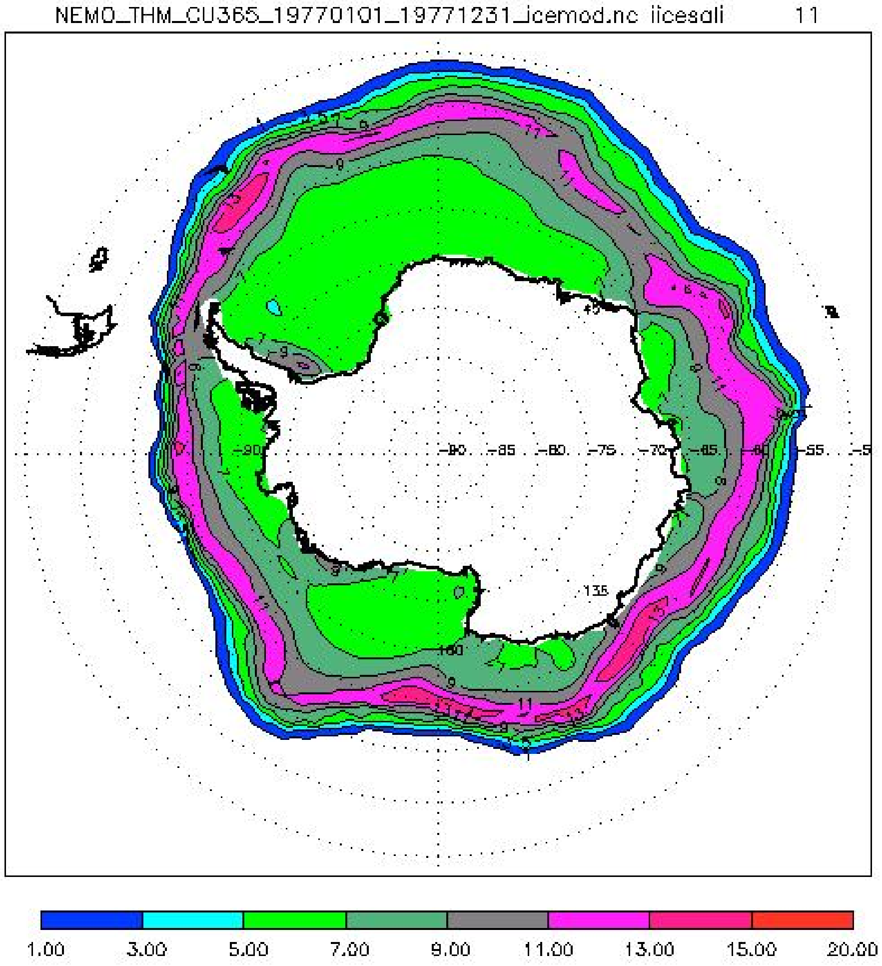


winter

Simplified salinity model (3D)



summer



winter

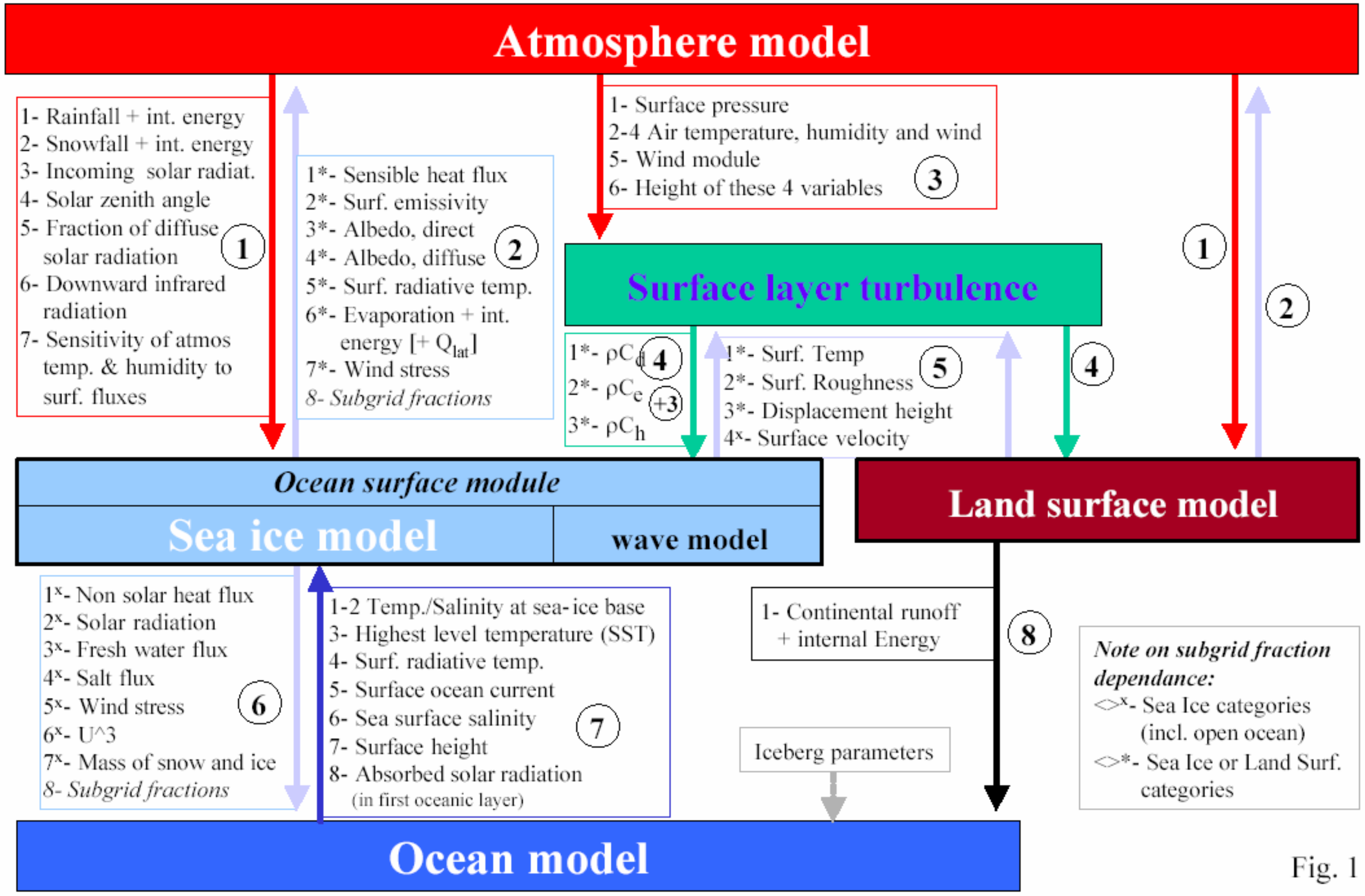
5. Coupled model design

Where should the sea ice interface be placed?

- Coupled models vary on where the sea ice interface is placed. For example:
  - CSIRO model has sea ice in atmosphere component
  - French coupled model has sea ice in ocean component
  - Hadley Centre coupled model has sea ice split between ocean and atmosphere

- Probably no ‘perfect solution’!

PRISM design



Atmosphere model

①
1- Rainfall + int. energy
2- Snowfall + int. energy
3- Incoming solar radiat.
4- Solar zenith angle
5- Fraction of diffuse solar radiation
6- Downward infrared radiation
7- Sensitivity of atmos temp. & humidity to surf. fluxes

②
1*- Sensible heat flux
2*- Surf. emissivity
3*- Albedo, direct
4*- Albedo, diffuse
5*- Surf. radiative temp.
6*- Evaporation + int. energy [+ Q_{lat}]
7*- Wind stress
8- Subgrid fractions

③
1- Surface pressure
2-4 Air temperature, humidity and wind
5- Wind module
6- Height of these 4 variables

Surface layer turbulence

④
1*- ρC_d
2*- ρC_e
3*- ρC_h
③ +3

⑤
1*- Surf. Temp
2*- Surf. Roughness
3*- Displacement height
4^x- Surface velocity

④ ① ②

Ocean surface module

Sea ice model | **wave model**

Land surface model

⑥
1^x- Non solar heat flux
2^x- Solar radiation
3^x- Fresh water flux
4^x- Salt flux
5^x- Wind stress
6^x- U^3
7^x- Mass of snow and ice
8- Subgrid fractions

⑦
1-2 Temp./Salinity at sea-ice base
3- Highest level temperature (SST)
4- Surf. radiative temp.
5- Surface ocean current
6- Sea surface salinity
7- Surface height
8- Absorbed solar radiation (in first oceanic layer)

⑧
1- Continental runoff + internal Energy

Iceberg parameters

Note on subgrid fraction dependance:
<>^{x}- Sea Ice categories (incl. open ocean)
<>*- Sea Ice or Land Surf. categories

Ocean model

Fig. 1

Eric Guilyardi (pers. comm.)

Considerations

- Boundary condition at bottom of atmosphere; Dirichlet or Neumann?
- Capturing the diurnal cycle
- Computational limits of coupling frequency between component models
- Resolving ocean-ice processes

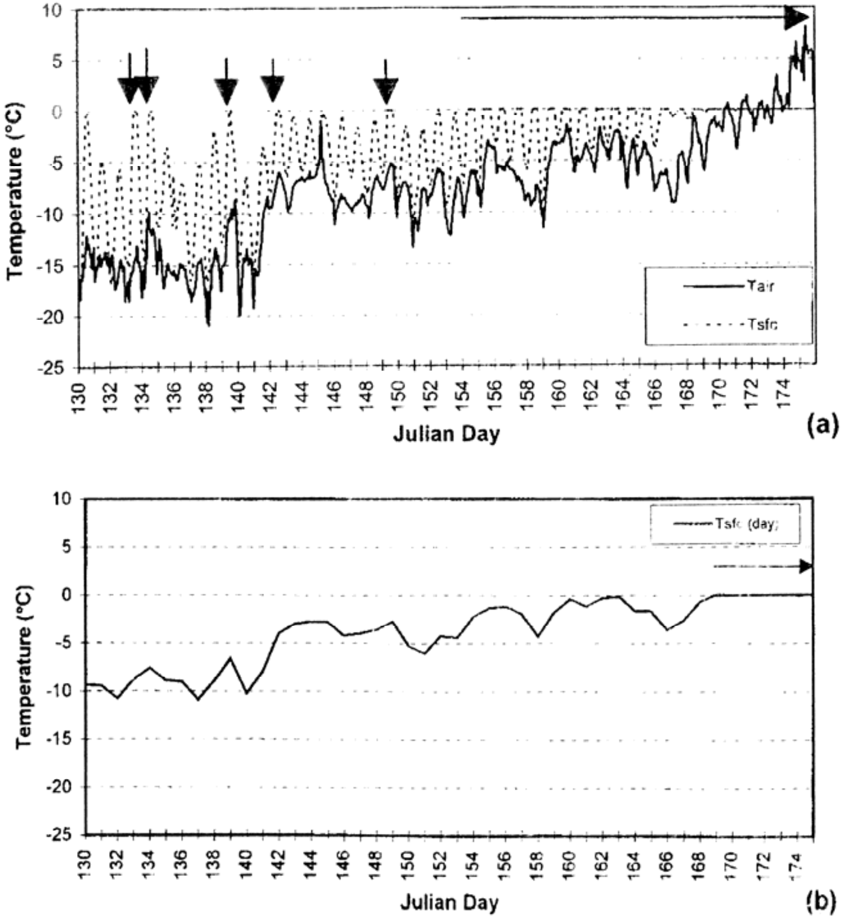
Boundary conditions

- At the top of the sea ice:
  - Fs (~To-Ts1)=Fa=Rnet-SH-LH
- If the bc's are Dirichlet:
  - atmospheric temperature profile calculated with To fixed from sea ice
  - Fs is therefore known
- If the bc's are Neumann:
  - Hs is required to solve atmospheric temperature profile (including To)
  - Ts1 needs to be passed from sea ice component

Diurnal cycle

- To capture variation in temperature over sea ice, frequent coupling is required between Fa, Fs, To and Ts1

Time series of Arctic spring (a) hourly forced modeled surface temperature (dotted line) and ambient air temperature (solid line) and (b) daily modeled surface temperature. Arrows indicate days with surface melt (from Hanesiak et al., 1999). Inclusion of diurnal cycle increases open water duration by 21 days



Coupling frequency

- Passing data between model components can increase the cost of the coupled model
- For example, going from daily to 3 hourly coupling in HadGEM1 increases the cost of the model by 10%
- Therefore need to design of the model to minimise the computational cost (eg, if sea ice is in ocean but needs to couple with atmosphere every timestep this would be an unreasonable overhead)

Ocean-ice processes

- Ocean grid generally finer than atmospheric grid. For example,
    - In HadCM3, the ocean is 6x atmosphere resolution
    - In HadGEM1, the ocean is 2.3x atmosphere resolution
- To resolve ocean-ice processes need to calculate sea ice properties (ice fraction, thickness, motion) on ocean grid

Hadley Centre type atmosphere models

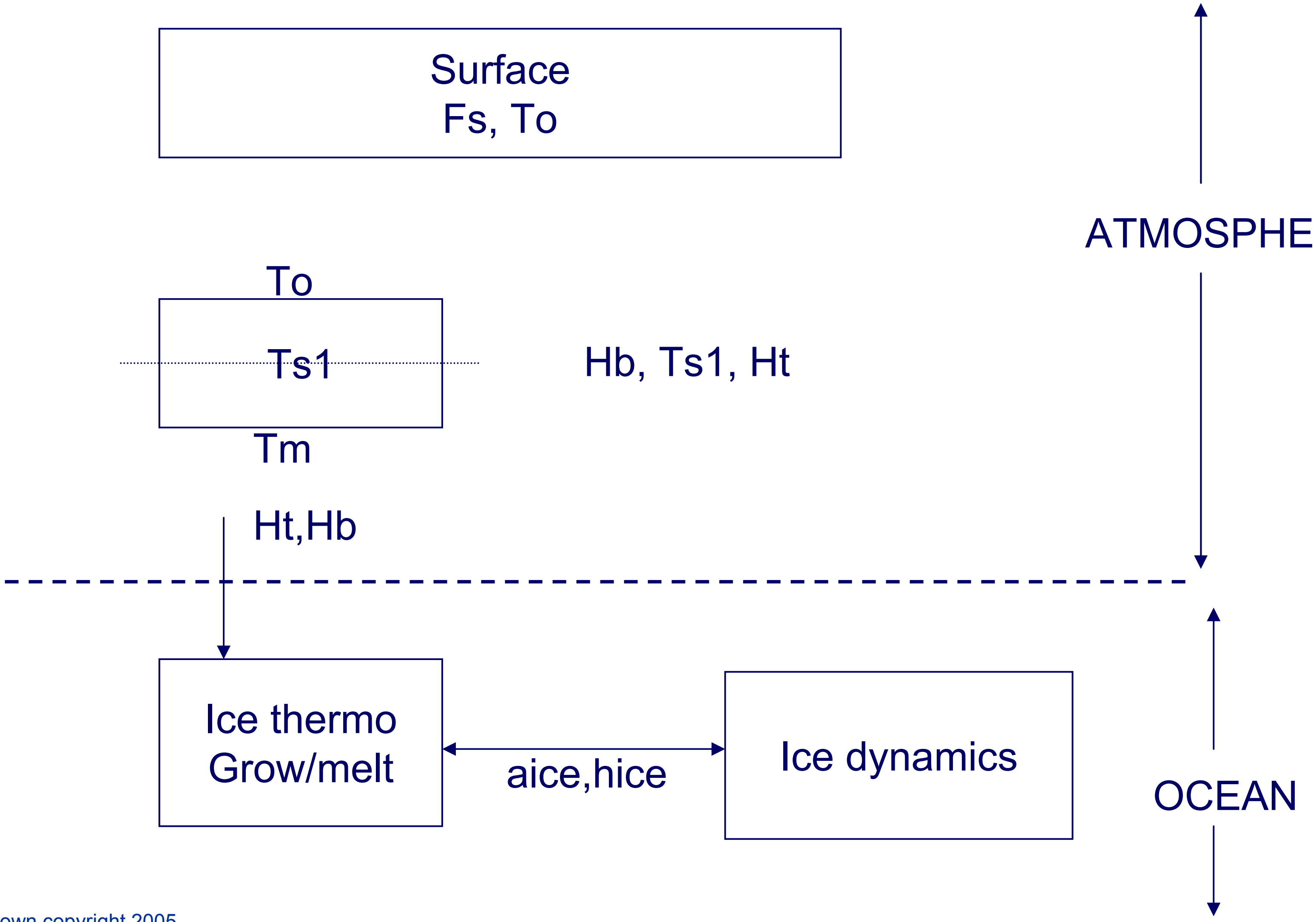
- In the Hadley Centre atmosphere model, the vertical temperature is solved as part of a tridiagonal matrix

- As described in Best et al. (2004), the surface temperature is then prescribed:

$$To=f(Ai,Bi,Hs)$$

Where Ai and Bi are coefficients in the tridiagonal matrix

HadCM3/HadGEM1 sea ice interfaces



Surface
Fs, To

ATMOSPHERE

To

Ts1

Tm

Hb, Ts1, Ht

Ht,Hb

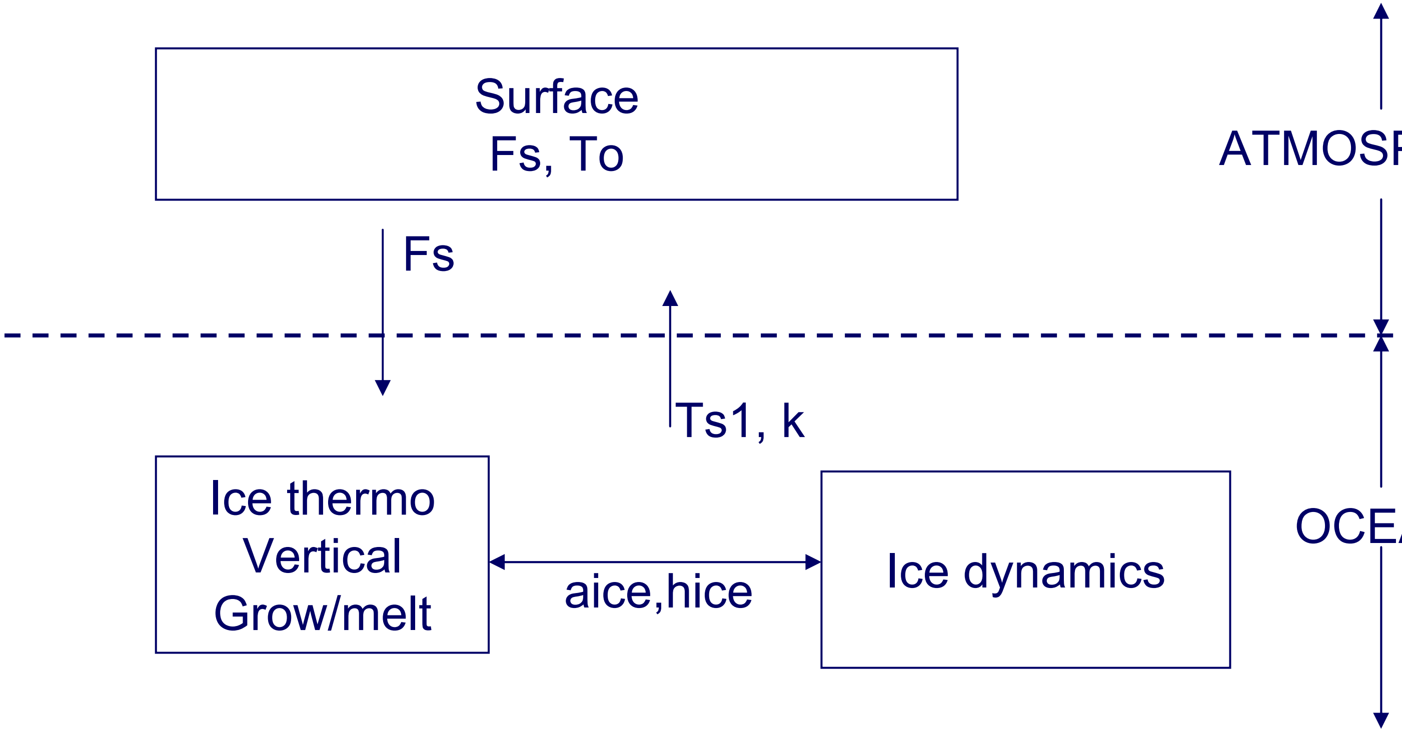
Ice thermo
Grow/melt

aice,hice

Ice dynamics

OCEAN

Moving to a multi-layer model with sea ice in ocean component



Surface
Fs, To

Fs

Ts1, k

ATMOSPHERE

Ice thermo
Vertical
Grow/melt

aice,hice

Ice dynamics

OCEAN

Ocean-atmosphere coupling may need to be frequent to ensure stability in the sea ice

6. Results from IPCC models

What is state of the art in sea ice modelling for climate?

- Data from 23 climate models has been submitted to IPCC AR4
- Obtained information on 20 sea ice components
- 11 multilayer models, 9 single layer models
- 7 multicategory models, 13 single category
- 2 no dynamics, 1 simple dynamics, 17 rheology (viscous-plastic or elastic-viscous-plastic)

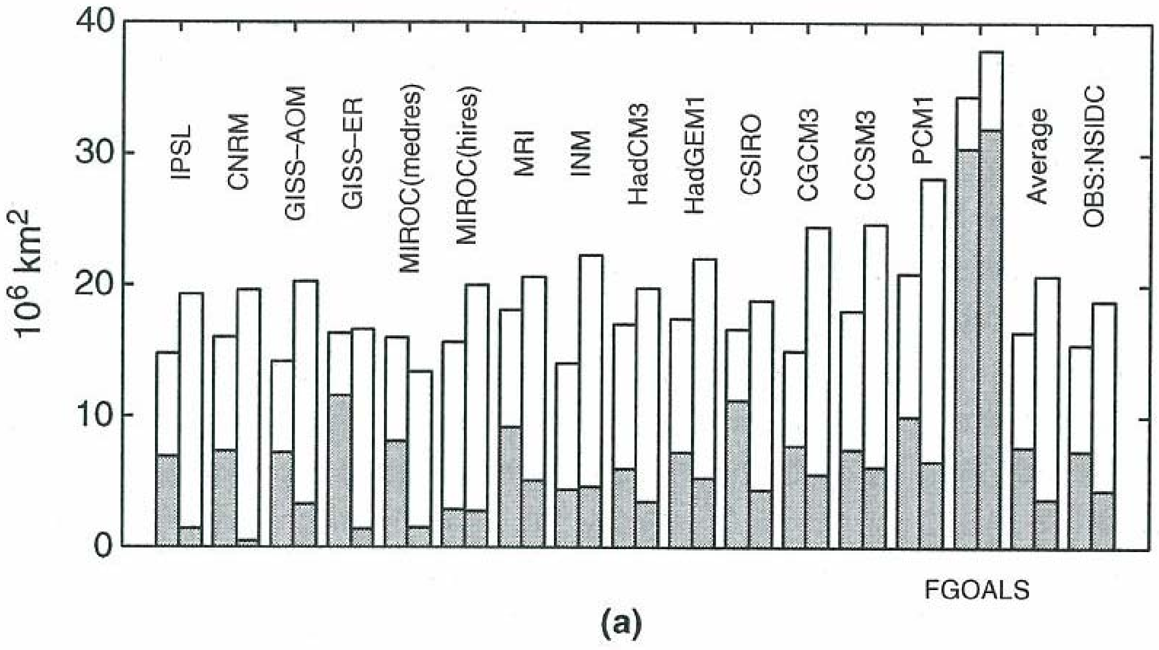
Climate model results

- Results from sea ice simulations with coupled models are sensitive to the atmosphere and ocean forcings

- For example, Arctic sea ice is highly sensitive to the details of the thermohaline circulation in the climate model

Distribution of Arctic sea ice extent

O. Arzel et al. / Ocean Modelling 12 (2006) 401–415



Ice extents

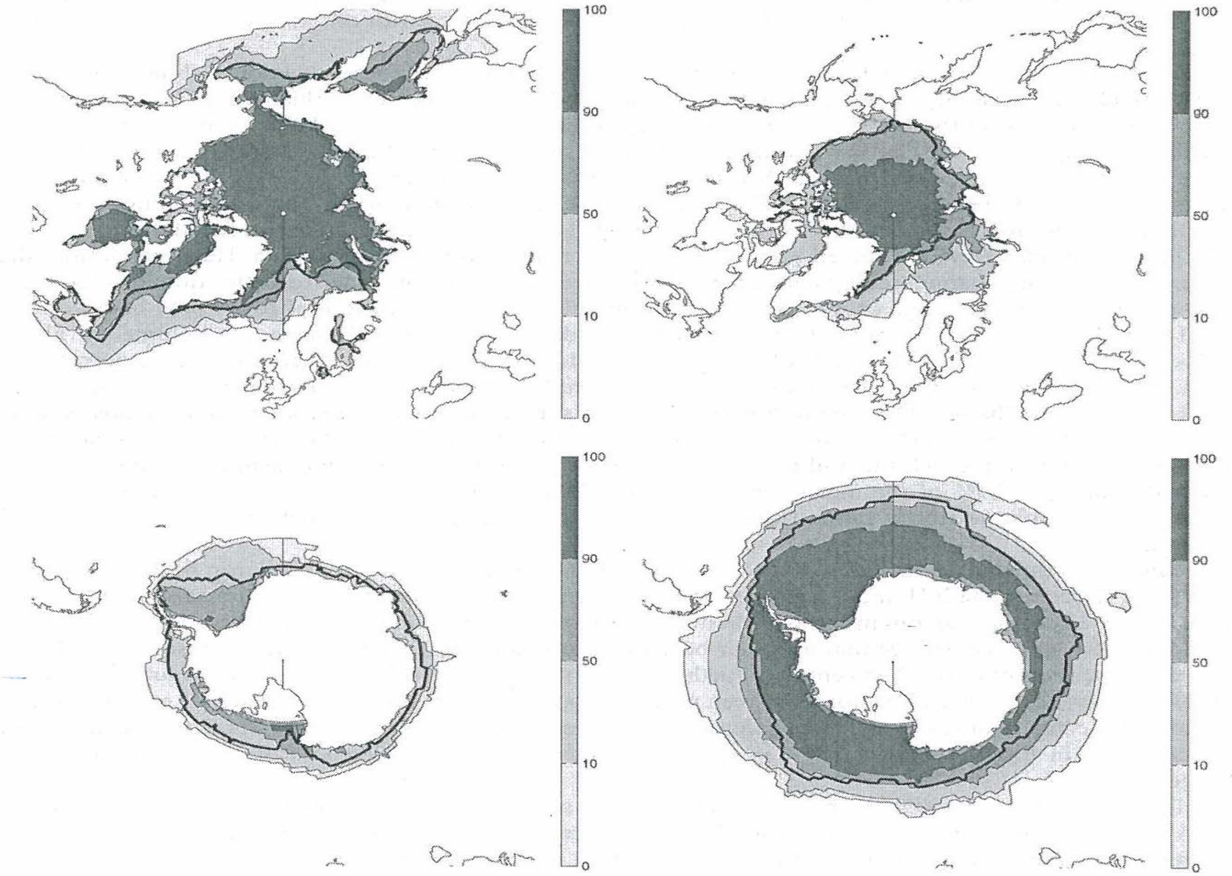
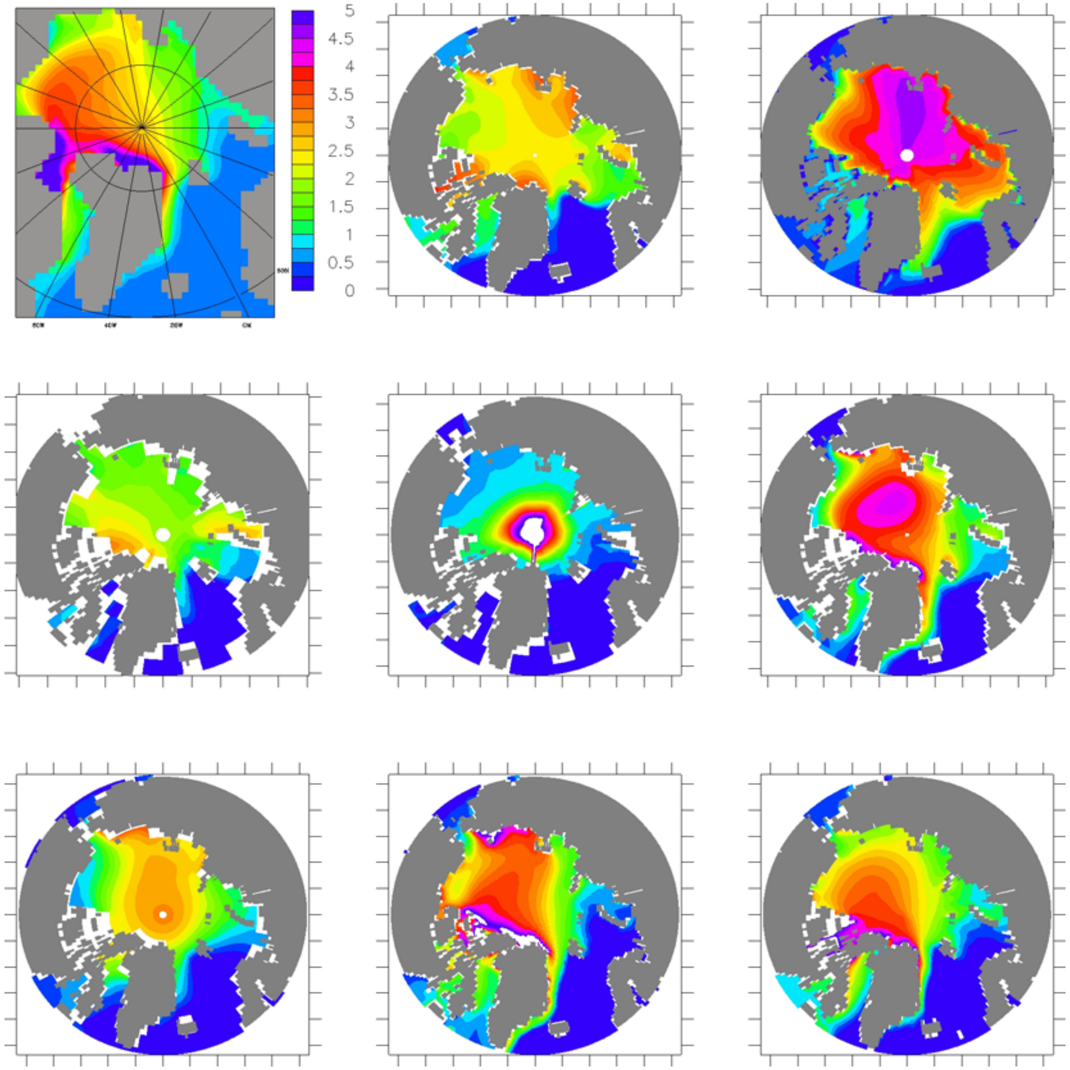


Fig. 2. Range of sea ice extent in the model simulations over 1981–2000 (20C3M experiment). Shading indicates the percentage (%) of models that have ice in average over the period 1981–2000 in March (left) and September (right) for both hemispheres. The analysis is based on 14 models (FGOALS-g1.0 excluded). The observed sea ice edge (thick black line) is based on the HadISST dataset (Rayner et al., 2003).

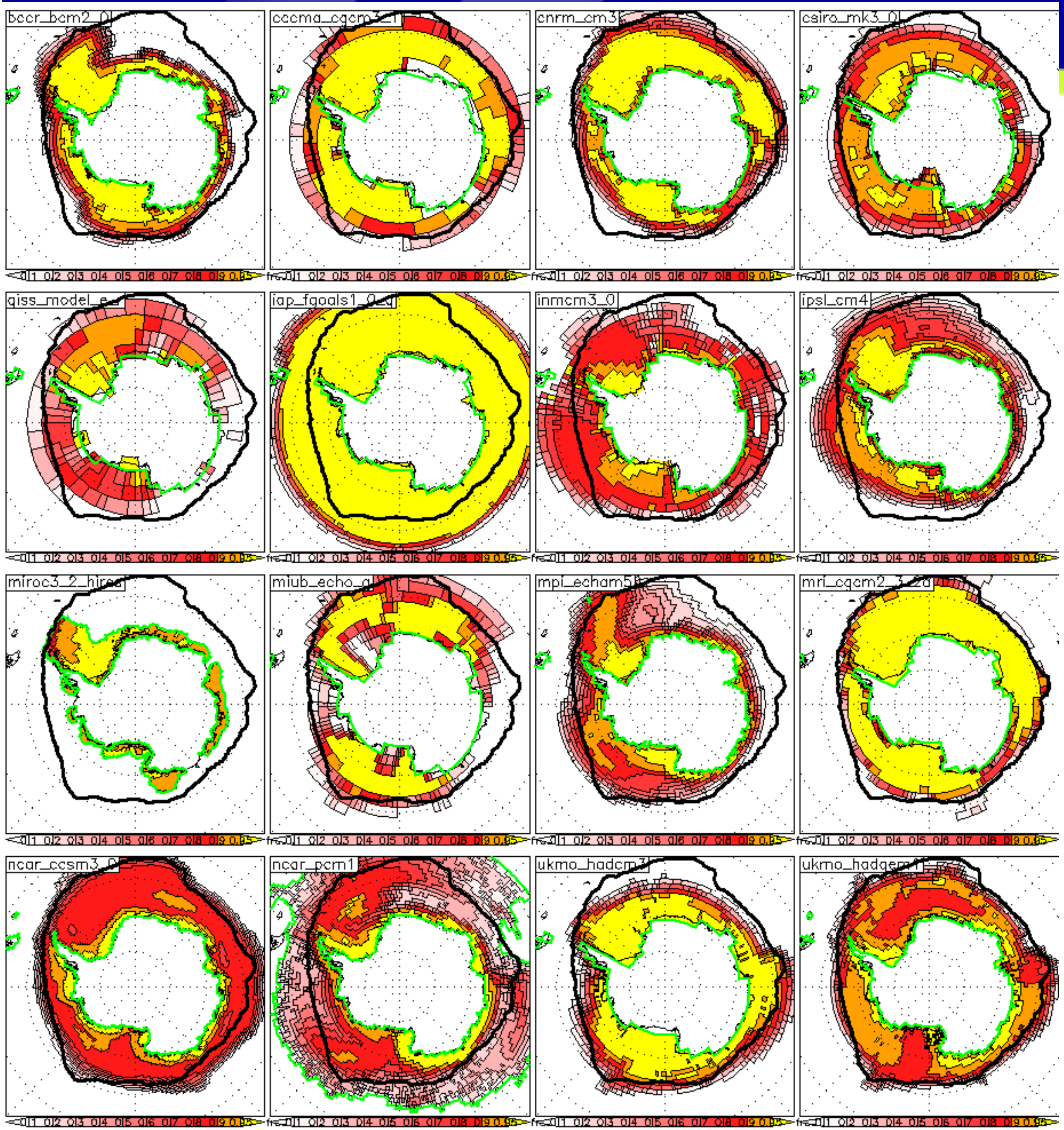
Arctic sea ice thickness: 1950-2000



Sea ice thickness for a range of models submitted to the IPCC 4th assessment report (AR4)

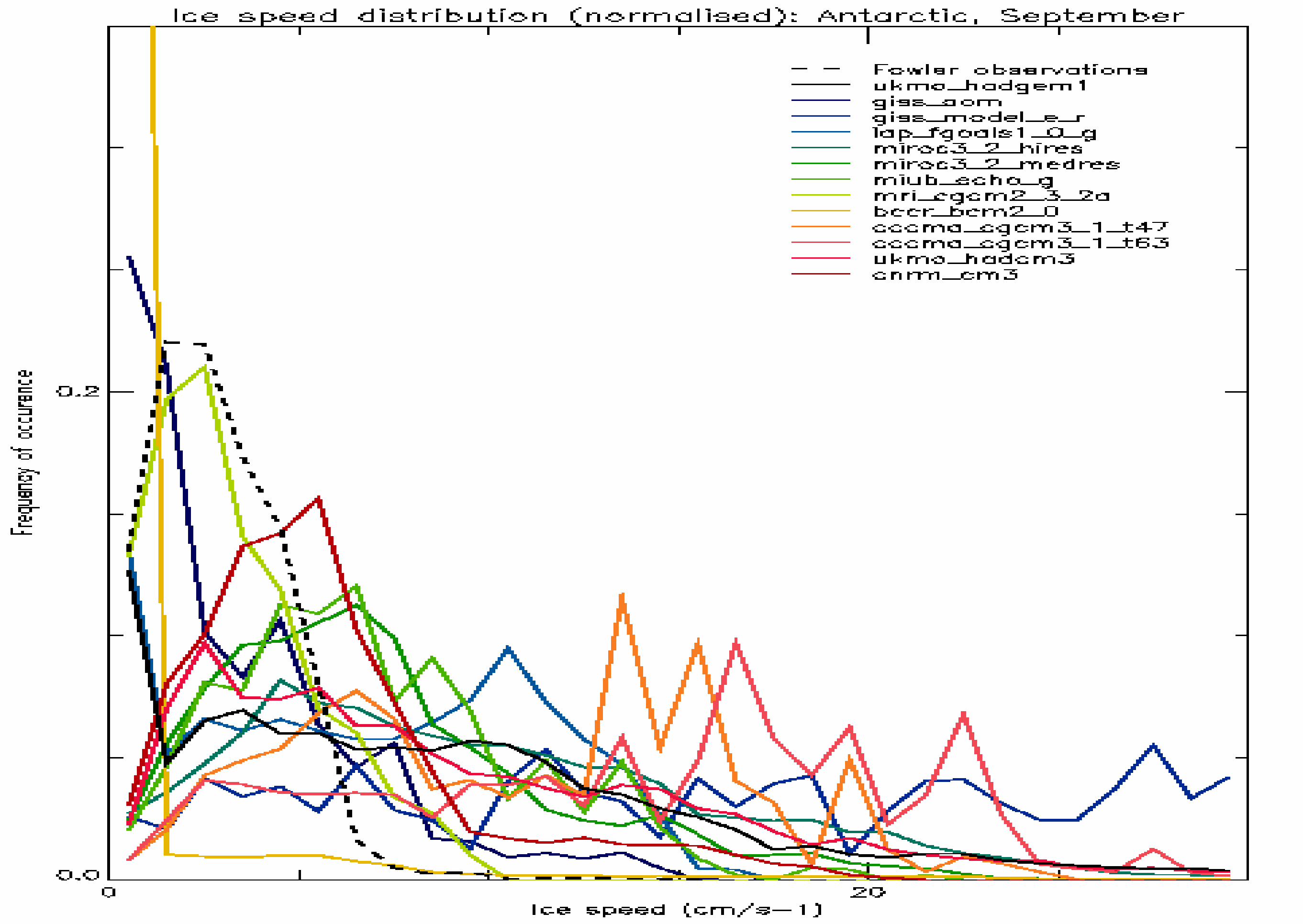
(courtesy of Gerdes and Köberle, submitted to JGR March 2006)

“The most realistic patterns are present in the CCSM and UKMO-HadGEM1 results”



September sea-ice concentration for 16 of the models submitted to the IPCC 4th assessment report (AR4)

(reproduced courtesy of William Connolley, BAS)



Distribution of ice speed in a number of climate models submitted to IPCC AR4

(Antarctic, September)

Ensemble average changes in ice extent

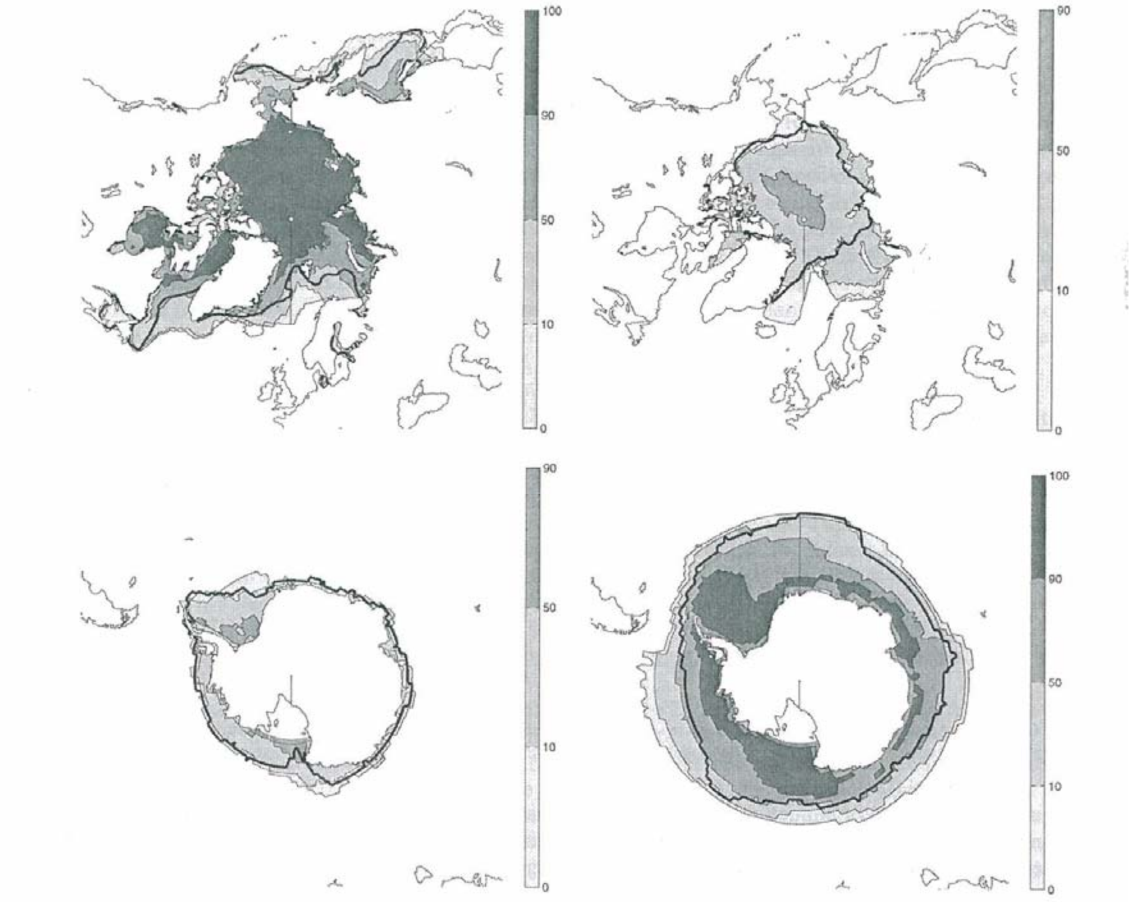
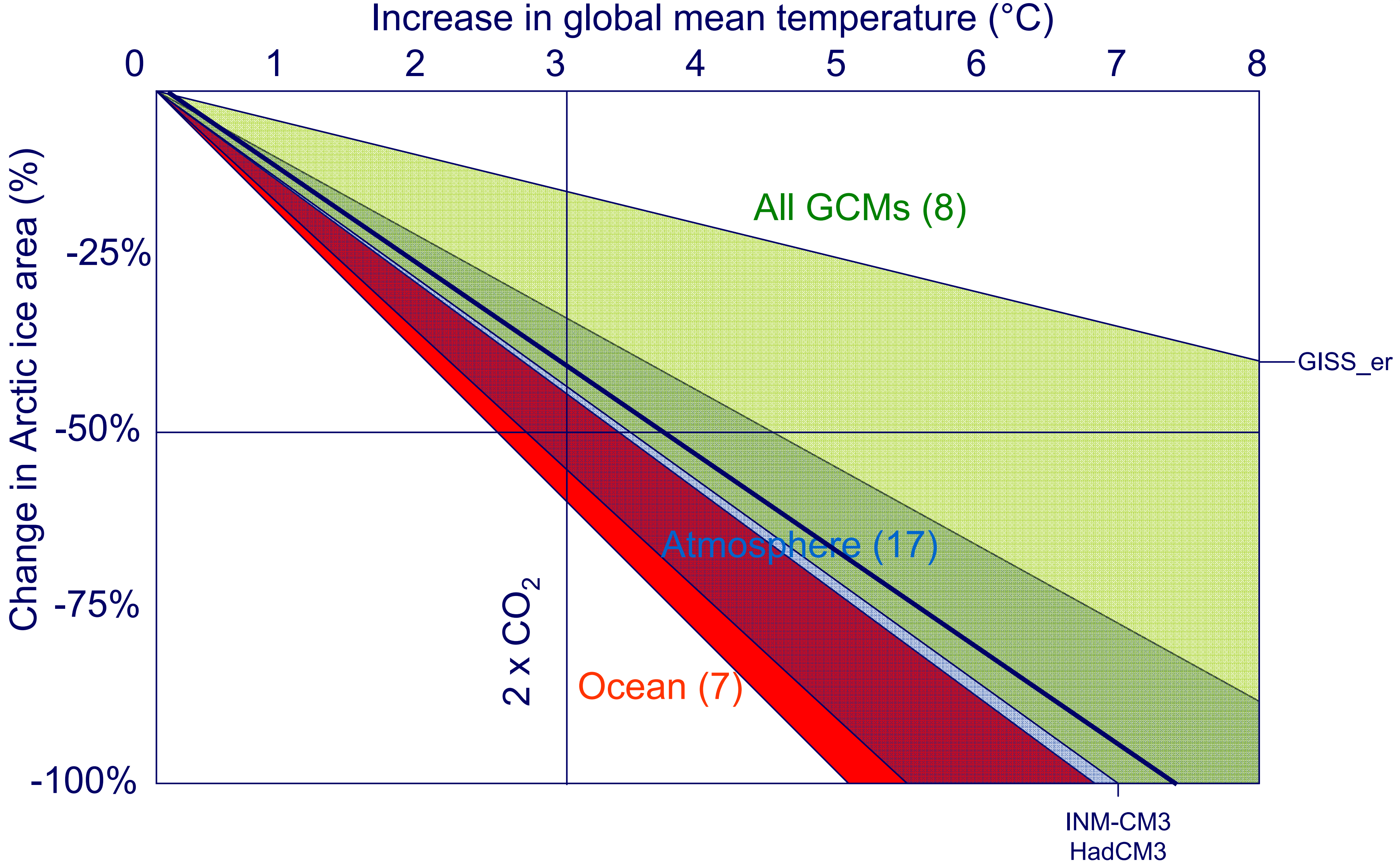
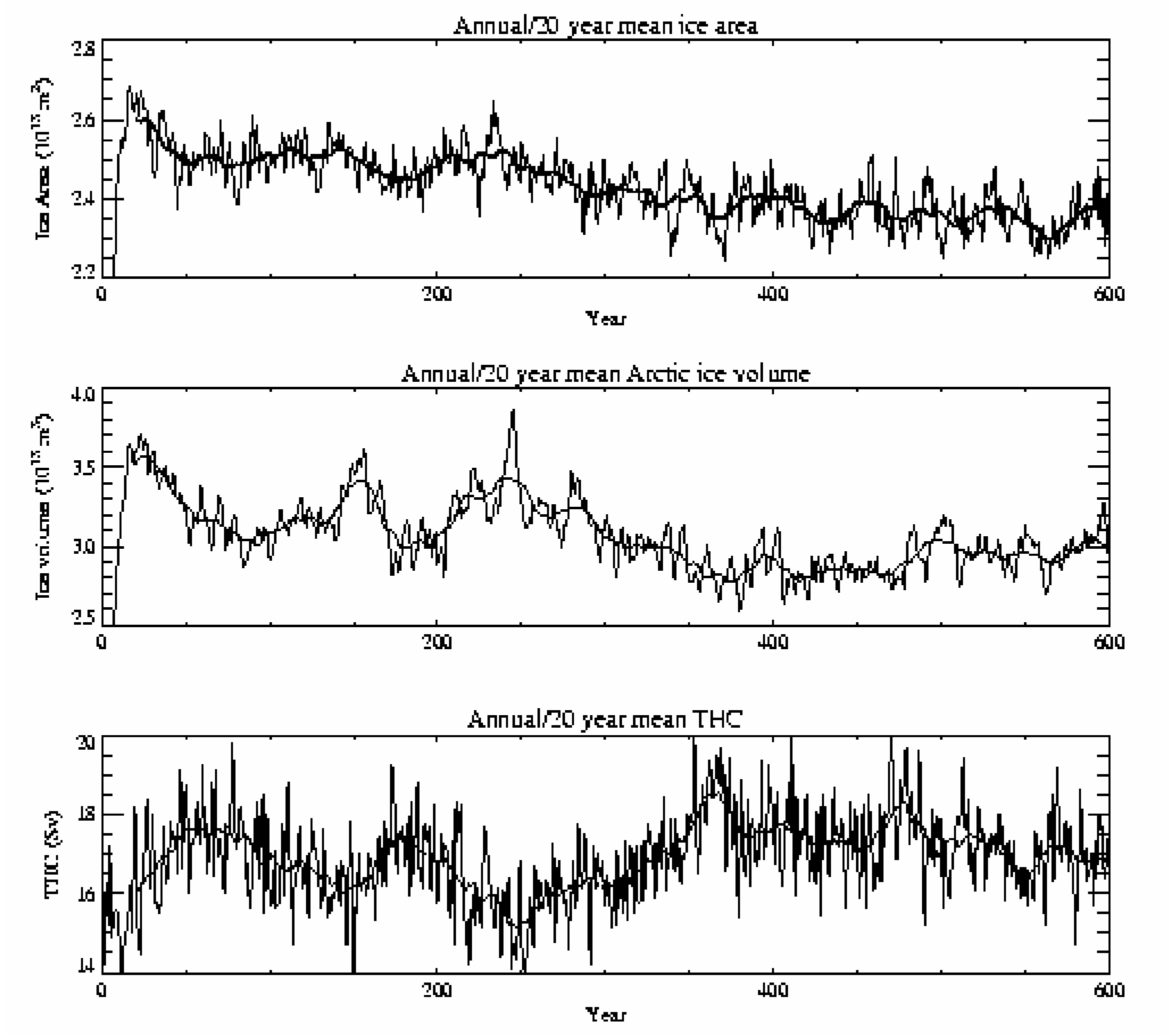


Fig. 4. Percentage (%) of models which have ice on average over the period 2081–2100 (experiment A1B) in March (left) and September (right) for both hemispheres (FGOALS-g1.0 excluded). The analysis is based on 10 models. For comparison, the thick black line represents the observed sea ice edge averaged over 1981– 2000, derived from the HadISST dataset (Rayner et al., 2003).

Arctic sea ice sensitivity



HadGEM1 ice variability



7. Conclusions

Conclusions

- State of the art in sea ice modelling for climate is:
  - multilayers
  - multicategories
  - sophisticated ice rheology
- The emerging choice for the position of the sea ice model is to place sea ice in the ocean component but tightly coupled to the atmospheric boundary layer

Future model developments

- Albedo:
  - Antarctic albedo changes dependant on the metamorphosis of snow, hence we need to include a good snow model (and the same snow model as used over land!)
  - Arctic albedo changes dependant on the temporal evolution of meltponds, hence we need an explicit model of the ponds to replace simplistic empirical parameterisations
- Ocean-ice fluxes:
  - Determining ocean-ice heat fluxes in the marginal ice zone
  - Constraining ice velocities-coupling to ocean

Future evaluation

- Mean state:
  - Evaluate against an increasing range of observations; concentration, thickness, velocities, ice types
- Variability:
  - Evaluate variability of sea ice on all timescales- requires ongoing semi-operational observations
- Multi-model ensemble:
  - Enhance confidence in results and eliminate some ‘tuning’ choices