Los Alamos
NATIONAL LABORATORY

CLIMATE, OCEAN AND SEA ICE MODELING PROGRAM

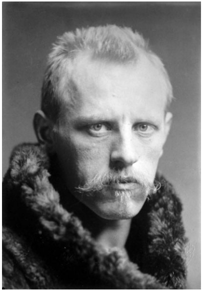
Sea Ice Modeling

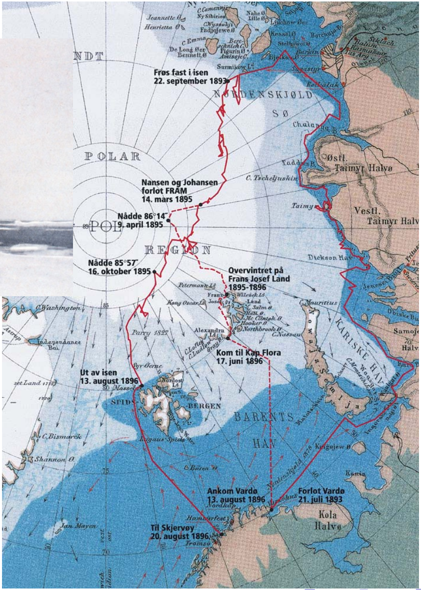
Elizabeth Hunke

October 20, 2009

Outline

Fridtjof Nansen and the Fram, 1893–1896

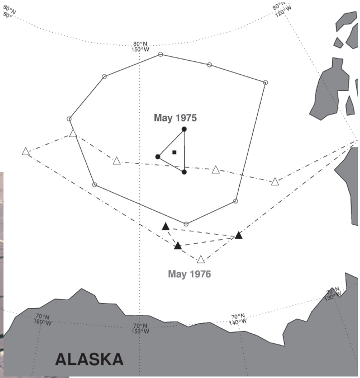




Ernest Shackleton, H.M.S. Endurance, 1914–1917

Ernest Shackleton, H.M.S. Endurance, 1914–1917

Arctic Ice Dynamics Joint Experiment, 1970–1978



Sea Ice Modeling Comes of Age

VOL. 76, NO. 6 JOURNAL OF GEOPHYSICAL RESEARCH FEBRUARY 20, 1971

1971

Some Results from a Time-Dependent Thermodynamic Model of Sea Ice[1]

GARY A. MAYKUT AND NORBERT UNTERSTEINER

Department of Atmospheric Sciences and Geophysics Program
University of Washington, Seattle 98105

A one-dimensional thermodynamic model of sea ice is presented that includes the effects of snow cover, ice salinity, and internal heating due to penetration of solar radiation. Surface-energy balances determine rates of ablation and accretion; diffusion equations govern heat transport within the ice and snow. The incoming radiative and turbulent fluxes, oceanic heat flux, ice salinity, snow accumulation, and surface albedo are specified as functions of time. Starting from an arbitrary initial condition, the model is integrated numerically until annual equilibrium patterns of temperature and thickness are achieved. The model is applied

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VOL. 80, NO. 33 JOURNAL OF GEOPHYSICAL RESEARCH NOVEMBER 20, 1975

1975

The Thickness Distribution of Sea Ice

A. S. THORNDIKE, D. A. ROTHROCK, G. A. MAYKUT, AND R. COLONY

University of Washington, Seattle, Washington 98195

The polar oceans contain sea ice of many thicknesses ranging from open water to thick pressure ridges. Since many of the physical properties of the ice depend upon its thickness, it is natural to expect its large-scale geophysical properties to depend on the relative abundance of the various ice types. The ice pack is treated as a mixture whose constituents are determined by their thickness and whose composition is determined by the area covered by each constituent. A dimensionless function $g(h)$, the ice thickness distribution, is defined such that $g(h)\,dh$ is the fraction of a given area covered by ice of thickness greater than h but less than $h + dh$. A theory is developed to explain how the ice thickness distribution changes in response to thermal and mechanical forcing. The theory models the changes in thickness due to melting and freezing and the rearrangement of existing ice to form leads and pressure ridges. In its present form the model assumes as inputs a growth rate function and the velocity field of the ice pack. The model is tested using strain data derived from the positions of three simultaneous manned drifting stations in the central Arctic during the period 1962–1964 and growth rates inferred from climatological heat flux

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The Energetics of the Plastic Deformation of Pack Ice by Ridging

D. A. ROTHROCK

University of Washington, Seattle, Washington 98105

A large-scale area of pack ice contains ice of various thicknesses from zero to many meters. As the area deforms, thin ice is ridged into thicker ice, in a way that depends on the strain rate and the instantaneous thickness distribution. By equating the plastic work to the production of gravitational potential energy and the frictional dissipation in this ridging process we relate the yield curve for plastic deformation of the ice pack to the way ice thicknesses are redistributed by ridging.

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JULY 1979 W. D. HIBLER III 815

1979

A Dynamic Thermodynamic Sea Ice Model

W. D. HIBLER III[1]

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755

(Manuscript received 1 May 1978, in final form 13 December 1978)

ABSTRACT

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JULY 1987 W. D. HIBLER III AND K. BRYAN 987

1987

A Diagnostic Ice–Ocean Model

W. D. HIBLER III

Thayer School of Engineering, Dartmouth College, Hanover, NH 03755

K. BRYAN

Geophysical Fluid Dynamics Laboratory, Princeton University, Princeton, NJ 08540

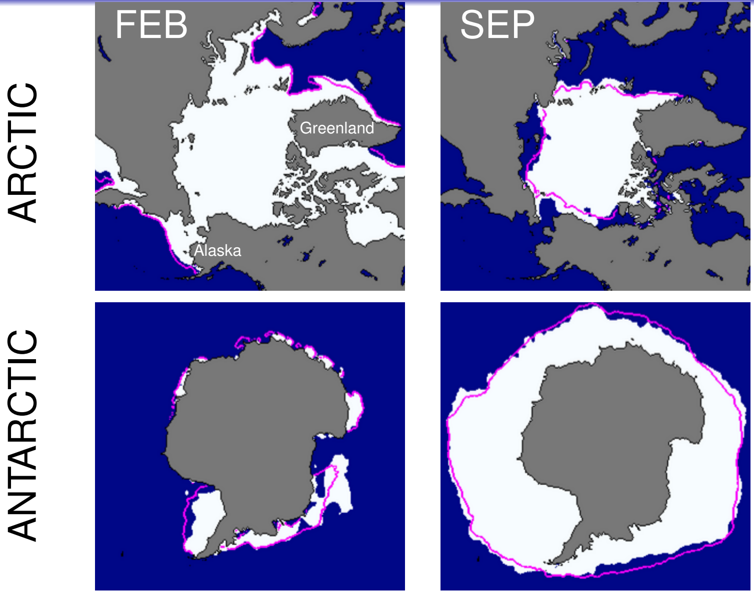
What's important?

E. Hunke

What's important? ALBEDO

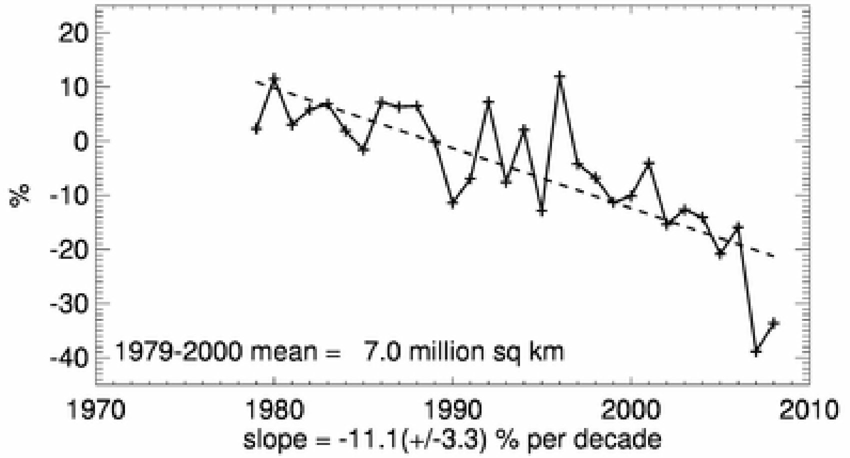
E. Hunke

Sea Ice Extent



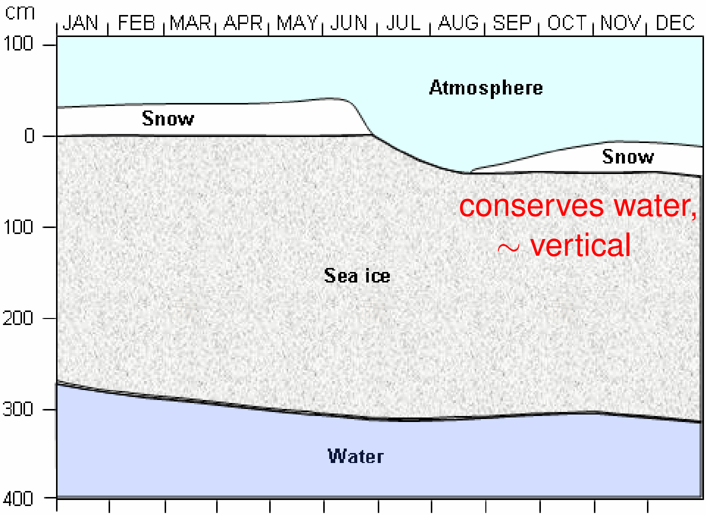
Images courtesy National Snow and Ice Data Center

September Arctic sea ice extent anomalies



National Snow and Ice Data Center

Thermodynamics

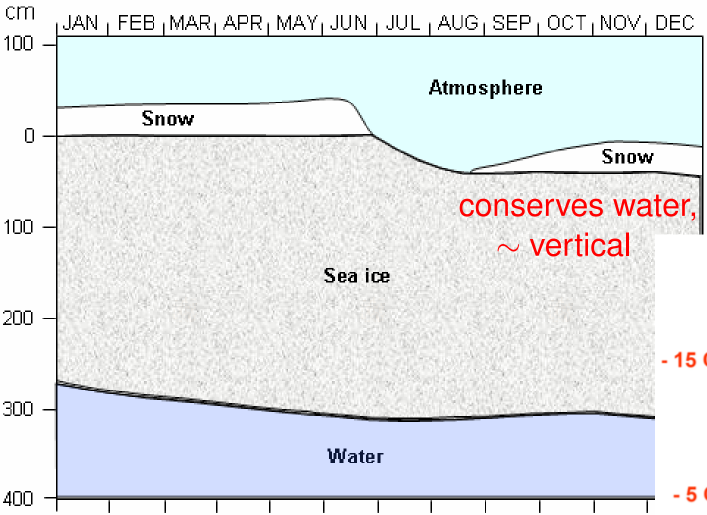


conserves water, salt, energy

$\sim$ vertical

National Snow and Ice Data Center

Thermodynamics



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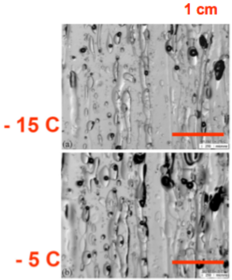
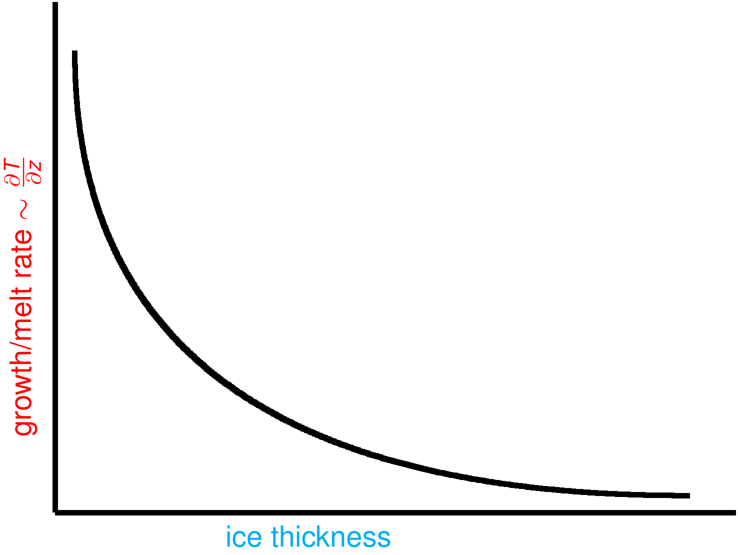


D. Pringle, Univ. of Alaska Fairbanks

Brine inclusions

National Snow and Ice Data Center


growth/melt rate $\sim \frac{\partial T}{\partial z}$
ice thickness

Ice Thickness Distribution

Dynamics


North America
Asia
Beaufort Gyre
Transpolar Drift
Fram Strait
Europe

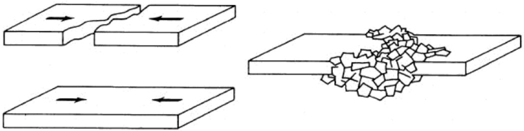
Dynamics

Sea Ice

- diverges freely
- resists convergence
- deforms under high enough pressure
- strength depends on area concentration, thickness

Deformation determines

- ice thickness distribution
- open water exposed to the atmosphere



(From Sanderson, 1988)

Dynamics

Momentum equation scale analysis for Baltic Sea drift ice†

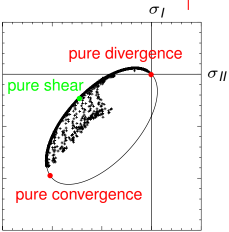
Term	Scaling	10^n N/m^2	
Local acceleration	$\frac{\rho HU}{T}$	-3	-2 for rapid changes
Advective accel.	$\frac{\rho HU^2}{L}$	-4	long term larger?
Coriolis	ρHfU	-2	generally $<$ -1
Internal ice stress	$\frac{P^* H}{L}$	-1	compact drift ice
Air stress	$\rho_a C_a U_a^2$	-1	
Water stress	$\rho_w C_w U_w^2$	-1	
Pressure gradient	ρHfU_w	-3	generally $<$ -2

†following M. Leppäranta in *Scaling Laws in Ice Mechanics and Ice Dynamics*, J. P. Dempsey and H. H. Shen, eds., Kluwer 2001

Viscous-Plastic Dynamics

$$m\frac{\partial u_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + \tau_{ai} + \tau_{wi} + \epsilon_{ij3} m f u_j - mg\frac{\partial H_\circ}{\partial x_i}$$

momentum
internal stress
wind stress
ocean stress
Coriolis
sea surface tilting



$$\frac{1}{2\eta}\sigma_{ij} + \frac{\eta - \zeta}{4\eta\zeta}\sigma_{kk}\delta_{ij} + \frac{P}{4\zeta}\delta_{ij} = \dot{\epsilon}_{ij}$$

Elastic-Viscous-Plastic Dynamics

$$m\frac{\partial u_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + \tau_{ai} + \tau_{wi} + \epsilon_{ij3} m f u_j - mg\frac{\partial H_\circ}{\partial x_i}$$

momentum

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ocean stress

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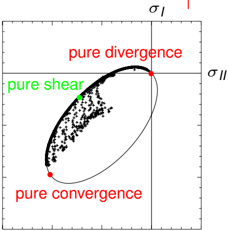

$$\frac{1}{E}\frac{\partial \sigma_{ij}}{\partial t} + \frac{1}{2\eta}\sigma_{ij} + \frac{\eta - \zeta}{4\eta\zeta}\sigma_{kk}\delta_{ij} + \frac{P}{4\zeta}\delta_{ij} = \dot{\epsilon}_{ij}$$

timescale $\quad \tau_e \sim \Delta x \sqrt{\frac{m}{E}}$

⋆ *EXPLICIT*

Continuum?

E. Hunke

CICE

Let's build a code...

variables/tracers
- ice area fraction
- ice/snow volume in each vertical layer
- ice/snow energy in each vertical layer
- surface temperature

CICE

Let's build a code...

variables/tracers
- ice area fraction
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- ice/snow energy in each vertical layer
- surface temperature

nonuniform, curvilinear, logically rectangular grids — dipole, tripole, regional
Fortran 90
parallelization via the Message Passing Interface (MPI) — cache-based decomposition

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Let's build a code...

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energy conserving, multi-layer thermodynamics (ice and snow)
ice thickness distribution with 5 categories and open water

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elastic-viscous-plastic (EVP) dynamics
incremental remapping advection
energy-based, multi-category ridging and ice strength
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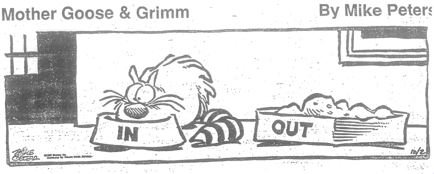
input/output options (format, frequency, type...) — coupling issues



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code repository and distribution	subversion
	many countries, dozens of institutions

CICE

Let’s build a code...

variables/tracers (for each thickness category)	
ice area fraction	ice age
ice/snow volume in each vertical layer	melt ponds
ice/snow energy in each vertical layer	algal ecosystem
surface temperature	
3D salinity	
energy conserving, multi-layer thermodynamics (ice and snow)	multiple-scattering radiation
ice thickness distribution with 5 categories and open water	ice bergs
elastic-viscous-plastic (EVP) dynamics	
incremental remapping advection	
energy-based, multi-category ridging and ice strength	
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CICE version 4.0

Let's build a code...

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- 3D salinity
- ice age
- melt ponds
- algal ecosystem

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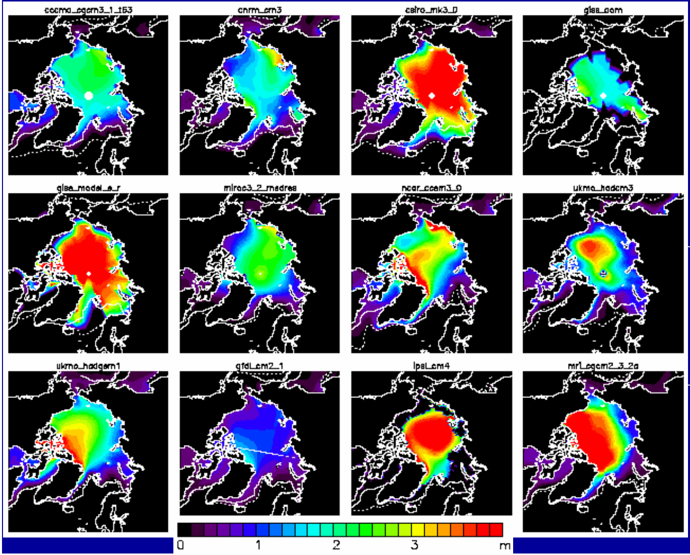
CICE wiki: http://oceans11.lanl.gov/trac/CICE

Some lessons from CCSM



Ann avg 1980-1999 ice thickness

IPCC AR4

Dash=March extent

White=Obs Extent

courtesy of M. Holland, NCAR

Some lessons from CCSM

An interim step forward: CCSM3.5

for tuning, biogeochemistry spin-up

Major changes/enhancements include:

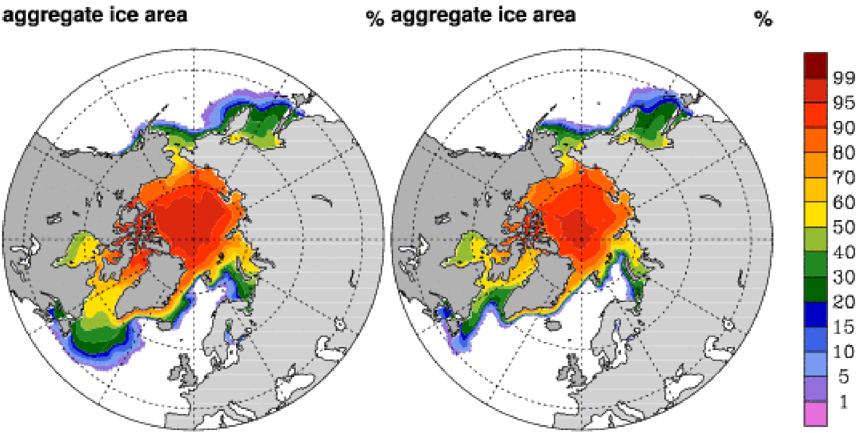
Atmospheric model
- finite volume dynamical core
- polar cloud parameterization

Ocean model
- near surface eddy flux scheme
- reduced viscosity
- 60 levels

Land model
- hydrology
- surface datasets

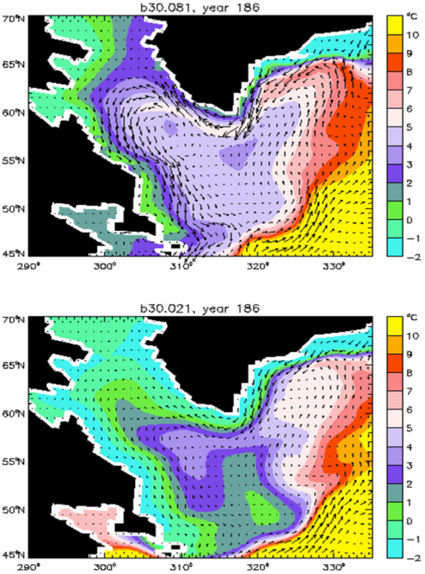
Sea Ice model
- ridging
- snow/melt ponds

Some lessons from CCSM



FV CCSM3

Some lessons from CCSM



FV2.2x1.9

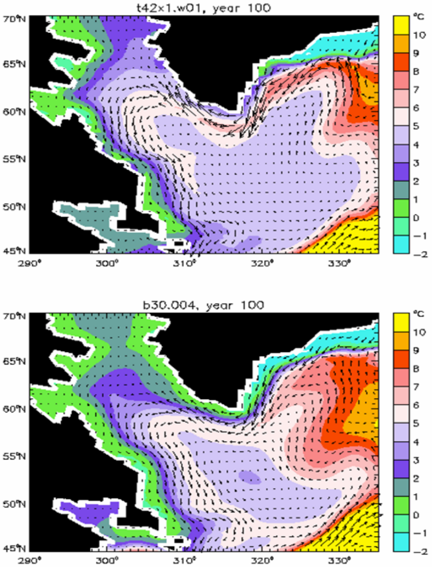
Without Smag

Temp and Velocity at 97 m.

With Smag

P. Gent, "State of the CCSM" address, June 2007

Some lessons from CCSM



CCSM3
T42x1

Without
Smag

Temp and
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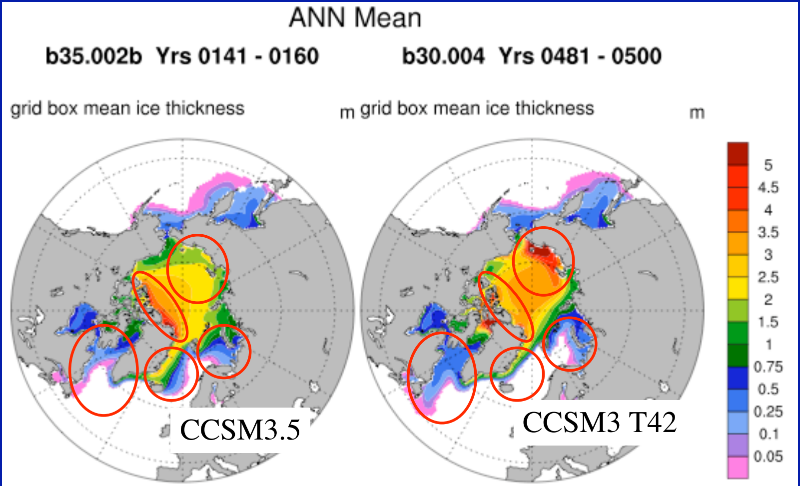
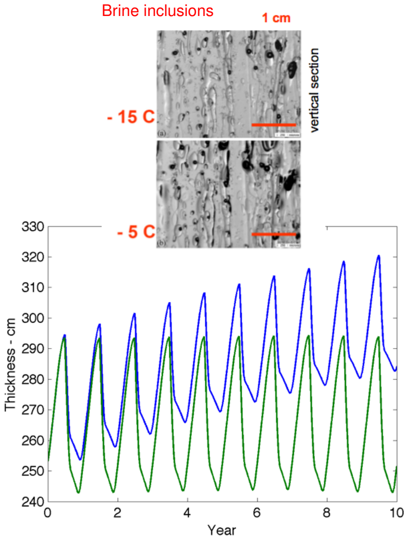


Arctic Sea Ice Thickness

courtesy of M. Holland, NCAR

Prognostic salinity



Green:
Well flushed
Ice bulk salinity
Currently
in CCSM

Blue:
Late spring
C-shaped
Bulk Salinity

- Cecilia Bitz

University of Washington

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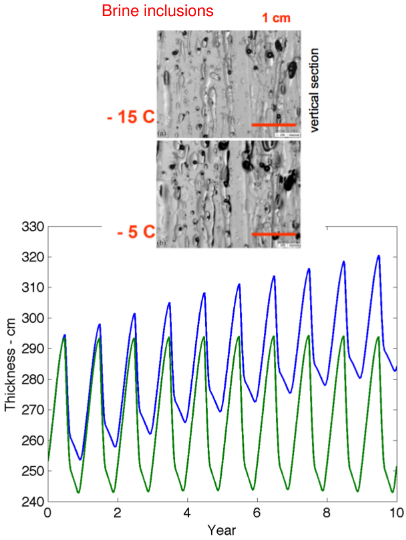

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- Postdoc

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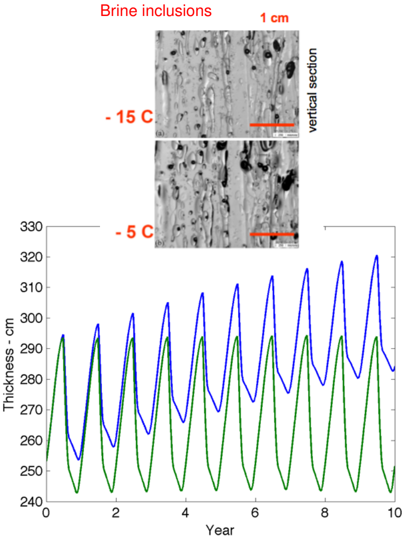


- Cecilia Bitz

  University of Washington
- Postdoc

  Los Alamos National Laboratory
- Wang Xiucheng

  Chinese Academy of Sciences

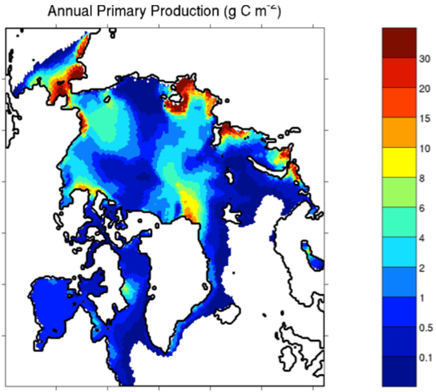
Sea Ice Ecosystem

- Scott Elliott
  Nicole Jeffery
  Mat Maltrud
  Elizabeth Hunke

  Los Alamos National Laboratory
- Clara Deal
  Meibing Jin

  IARC, U. of Alaska, Fairbanks

Sea Ice Ecosystem



- stand-alone CICE
- WOA nutrient climatology
- nitrate, silicate, ammonium, DMS(P)
- limiting by light, nutrients, melting
- coupled POP-CICE ecosystem in progress

Ice-ocean dynamic coupling approaches

ocean-ice stress τ_w = drag coef $\times$ quadratic $f(U_o - U_i)$

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$$\begin{aligned} \tau_o &= -\tau_w \\ &= \nabla \cdot \sigma + \tau_a - (\hat{k} \times mfU_i + mg\nabla H_\circ + m\frac{\partial U_i}{\partial t}) \end{aligned}$$

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2. ice-ocean stress = div(ice internal stress) + wind stress

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5. resolution of ocean boundary layer

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How much is necessary for climate modeling?

Ice bergs in CICE

- Lagrangian particles with finite size
- Berg momentum balance includes Coriolis, tilt, wind/ocean stresses, sea-ice dynamic interaction
- Sea ice ridging, momentum balance include berg interaction

E. Hunke

Ice bergs in CICE

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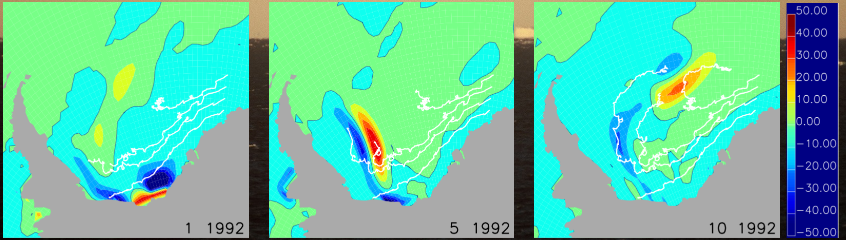
Change in sea ice thickness due to bergs, cm



E. Hunke

Snow

- compaction and densification
- granularization
- moisture transport
- wind redistribution
- slush and snow-ice...

Snow

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- granularization
- moisture transport
- wind redistribution
- slush and snow-ice...

Help needed!

Lessons in Humility

- The basic physical components were done decades ago.

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- My generation made them work together and with ocean, atmosphere components in climate models.

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Lessons in Humility

- The basic physical components were done decades ago.
- My generation made them work together and with ocean, atmosphere components in climate models.
- New physics directions are fun and exciting, but perhaps only higher-order effects (?)
- Bad atm/ocn forcing makes a bad sea ice simulation.
- Observationalists are modelers' heroes.

H.M.S. Endurance III

photography by E. Hunke