Tale of Two Sea-ice Models

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Outline

- **Sea ice model features**
  - Dynamics
  - Thermodynamics
- **Ice models in ROMS**
  - Budgell ice
  - CICE
- **Examples**
- **Future directions**

Dynamics

Momentum equation:

$$m\frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \sigma + \vec{\tau}_a + \vec{\tau}_w - \hat{k} \times mf\mathbf{u} - mg\nabla H_\circ$$

Assumptions:

- Continuum approximation
- Isotropic
- Viscous-plastic behavior
- Nonlinear advection is small

Isotropic?

Viscous-plastic?

- **Plastic means will be rigid under weak forces, will break under sufficiently strong pressure**
- **Assumed no tensile strength**
- **Viscous term for ease of solution**
  - Hibler's 1979 model had elliptic solver

Dynamics

Viscous-plastic term:

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

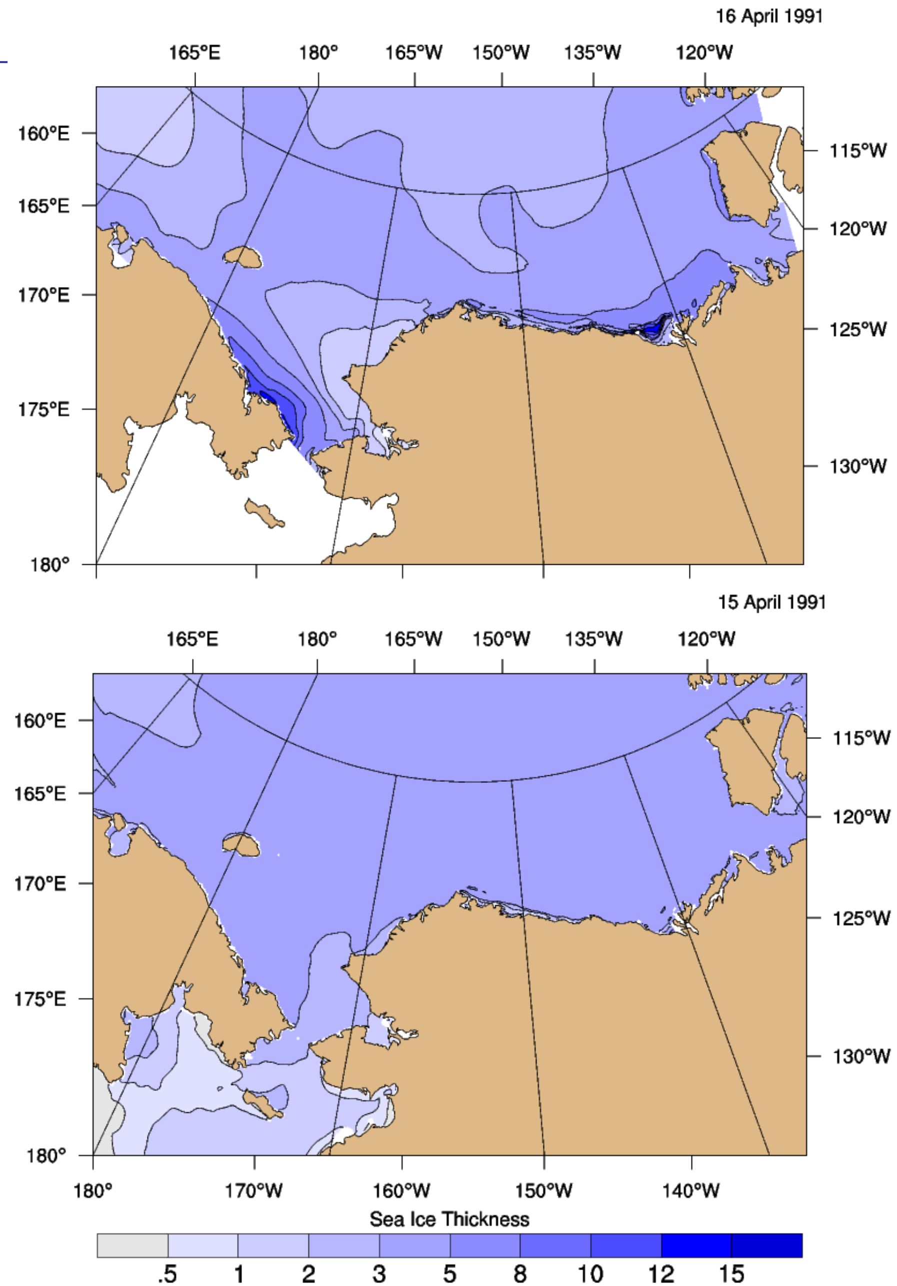
$$\dot{\epsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Ice strength – linear or quadratic?

$$P = P^* A h_i e^{-C(1-A)}$$

$$P = P^* A h_i^2 e^{-C(1-A)}$$

Ice Thickness



EVP Dynamics

- **Rearrange VP:**

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

- **EVP version:**

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

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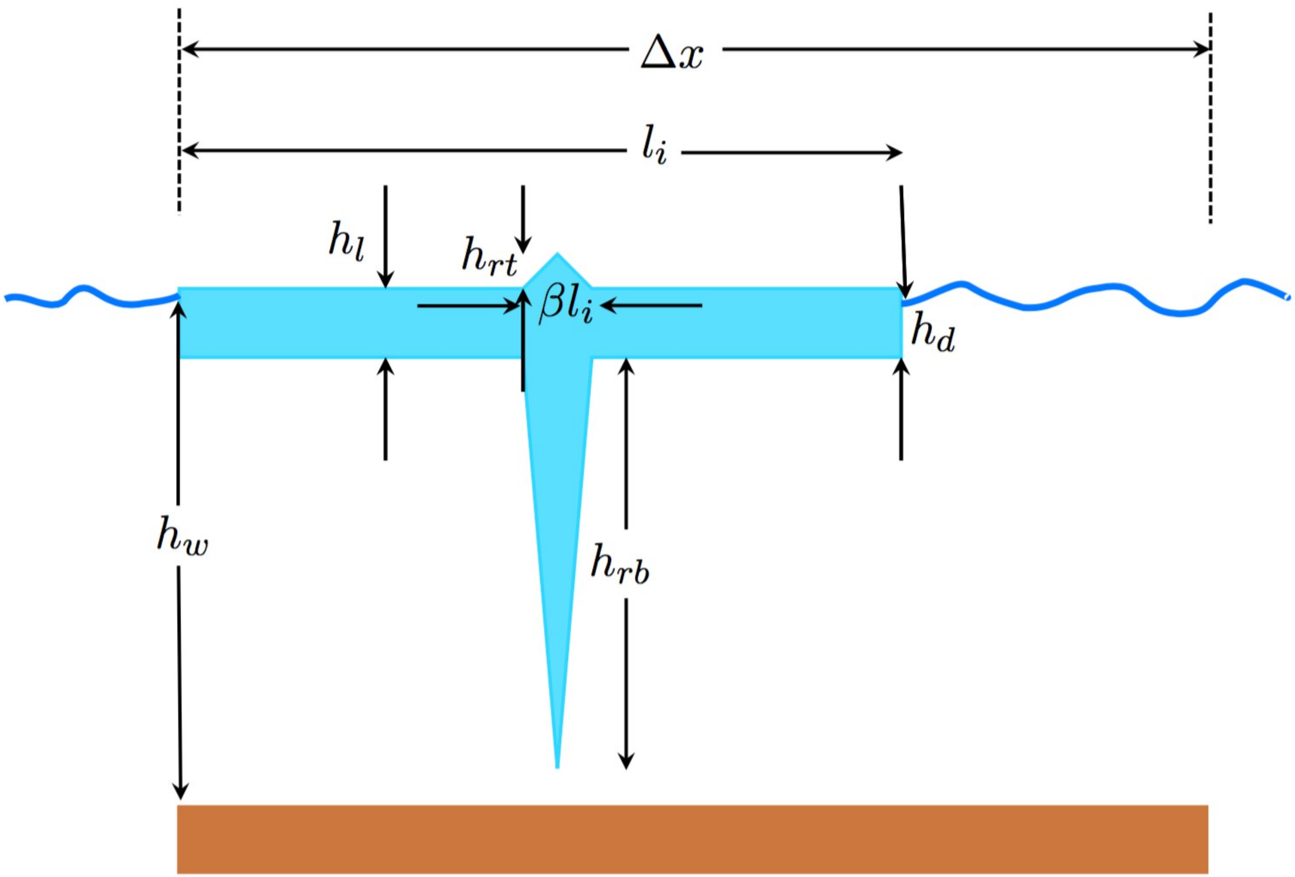
Solution

- Young's modulus E depends on ice thickness to keep solution close to VP solution
- Stress tensor equation is timestepped explicitly
- Ice velocities then timestepped with air/water stresses, Coriolis
- Since it is all explicit, easy to parallelize (domain decomposition)
- Iterate solution each baroclinic dt

Landfast Ice (Lemieux)



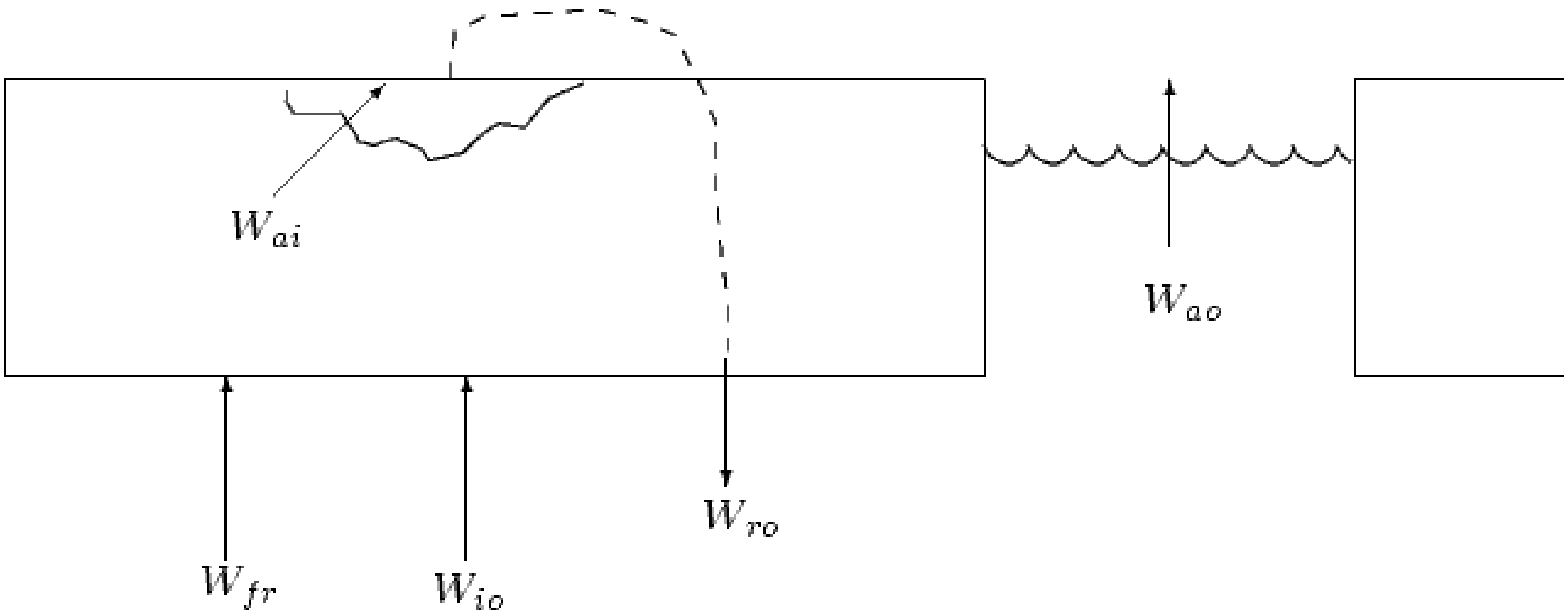
Basal Stress

- **Add a stress term which represents deepest keels dragging on the bottom**
- **Assume an ice thickness distribution**
- **U-momentum term:**

$$\tau_{bu} = \begin{cases} 0 & \text{if } h \le h_c, \\ k_2 \left(\frac{u}{|\vec{v}| + u_0} \right) (h - h_c) \exp^{-C_b(1-A)} & \text{if } h > h_c. \end{cases}$$

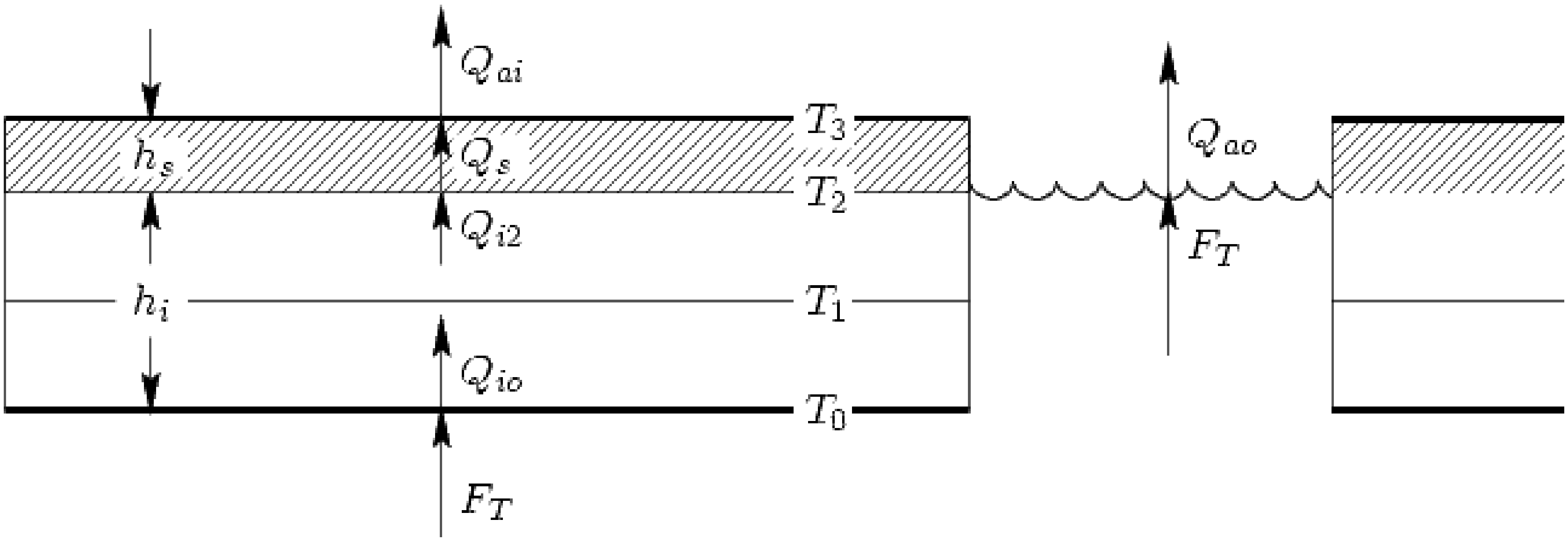
- **Some tunable parameters**
- **Next paper includes tensile strength**

Thermodynamics



Need to compute all the ice growth/melt terms shown

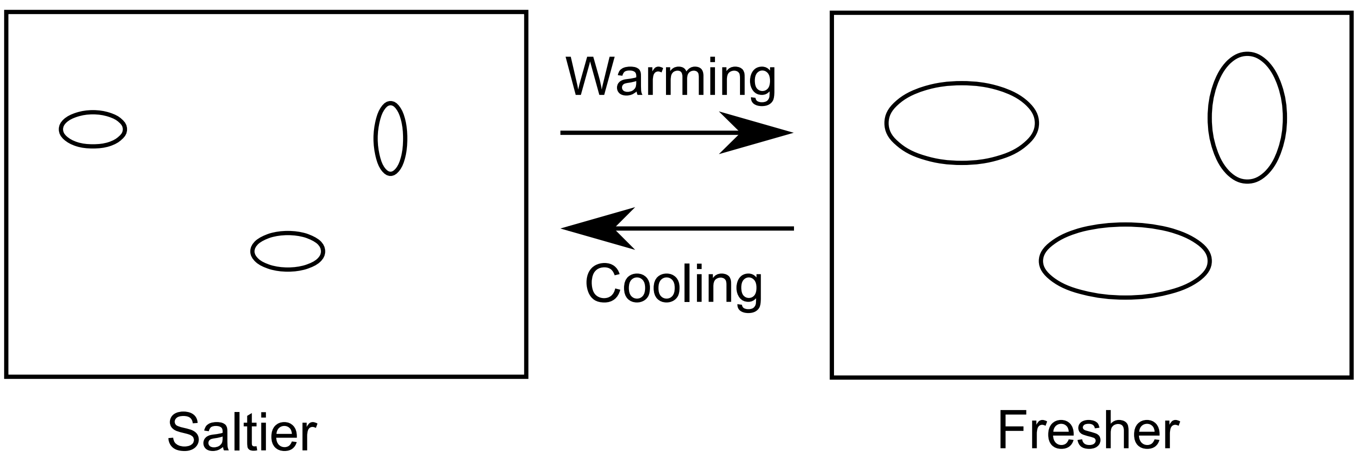
Thermodynamics



- **Heat fluxes are computed through the ice and snow**
- **Temperature profile is piecewise linear**

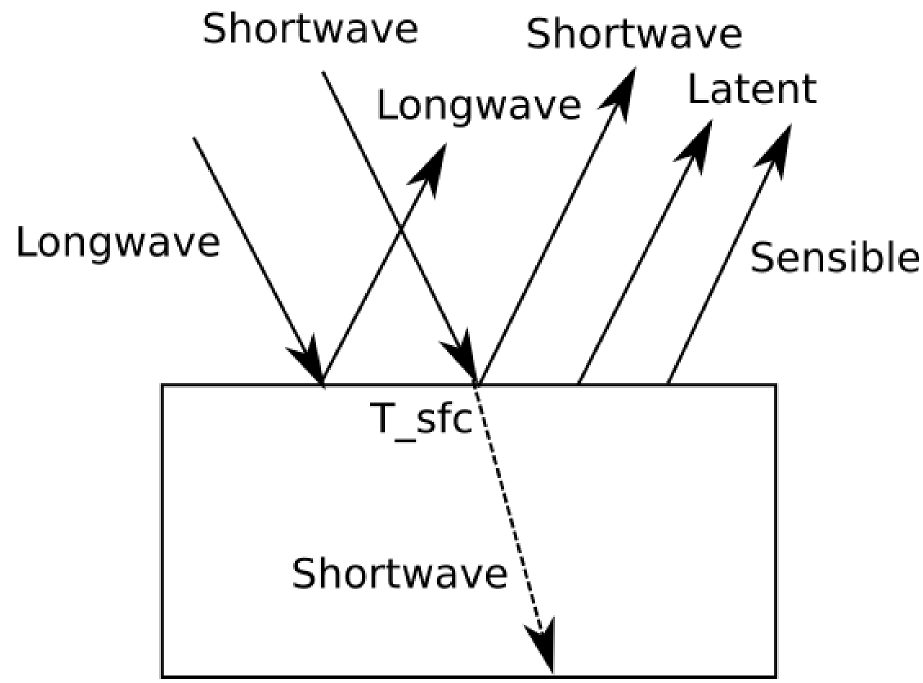
Brine Pockets

- **Need to track enthalpy of ice**
  - Brine pockets grow and shrink with warming and cooling: phase change



Thermodynamics

- **Solve for each ice thickness category:**
  - Surface temperature from surface heat fluxes
  - Heat flux through ice
  - Shortwave light penetration
  - Shortwave albedo depends on surface conditions



Thermodynamics

- **Snow ice formation**
  - When snow weighs down ice to submerge ice surface
  - Convert snow into ice
  - Budgell model could be more careful about salt conservation here...

Sea Ice Models

Budgell Ice

- **EVP dynamics**
- **Mellor-Kantha thermodynamics**
- **Single ice category, single layer**
- **Integral to ROMS (subroutine call)**
    - ROMS grid
    - ROMS timestep
    - Arakawa C-grid
    - ROMS tiling and nesting

Evolution of Tracers

$$\frac{DAh_i}{Dt} = \frac{\rho_o}{\rho_i}\left[A(W_{io} - W_{ai}) + (1-A)W_{ao} + W_{fr}\right]$$

$$\frac{DA}{Dt} = \frac{\rho_o}{\rho_i h_i}\left[\Phi(1-A)W_{ao} + (1-A)W_{fr}\right]$$

- **Ice volume is Ah_i**
- **Ice concentration is A,** $0 \le A \le 1$
- **Phi is tunable parameter, value depends on sign of Wao**

CICE (Hunke et al.)

- **EVP or EAP dynamics**
- **User chooses number of ice categories, layers, snow layers (compile time)**
- **Arakawa B-grid, own tiling, no nesting**
- **A few coupling options**
  - “Fake” coupler (subroutine call)
  - Metroms (MCT)
  - PolarCOAWST (MCT)

Pronunciation

"We pronounce the model name as "sea ice", but there has been a small grass-roots movement underway to alter the model name's pronunciation…"

- English "sice"
- French "cease"
- Japanese "shii-aisu"
- Italian "chee-chay"

- **Don't call it "sis"**

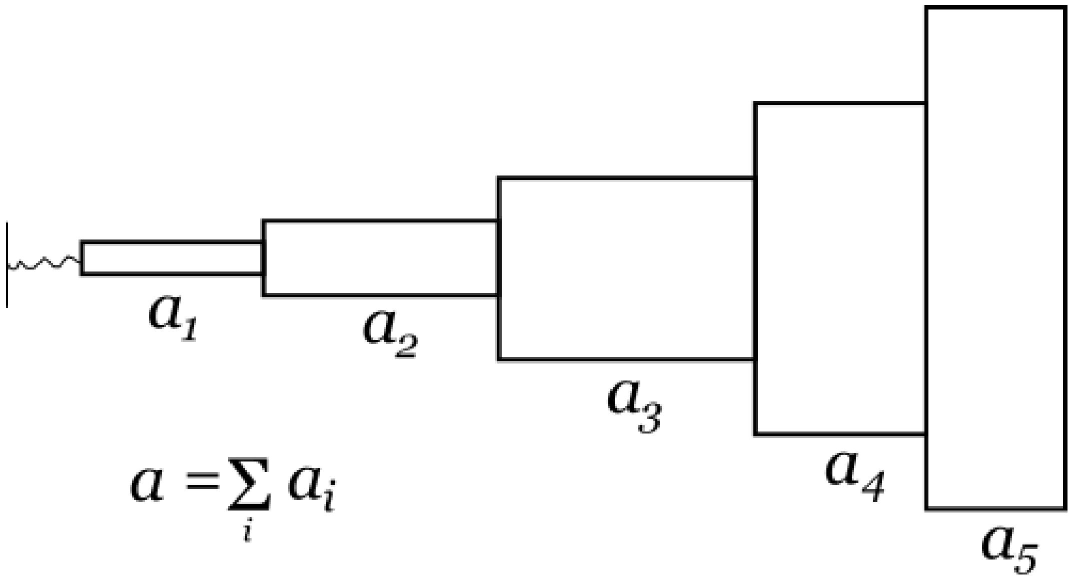
Fundamental CICE Equation

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

- $g(\mathbf{x}, h, t)\, dh$ **is the ice thickness distribution function**
- **u is velocity vector**
- f **is the rate of thermodynamic ice growth**
- ψ **is the ridging redistribution function**

Ice Thickness Distribution

- **Each cell has a number of different ice thicknesses and open water**

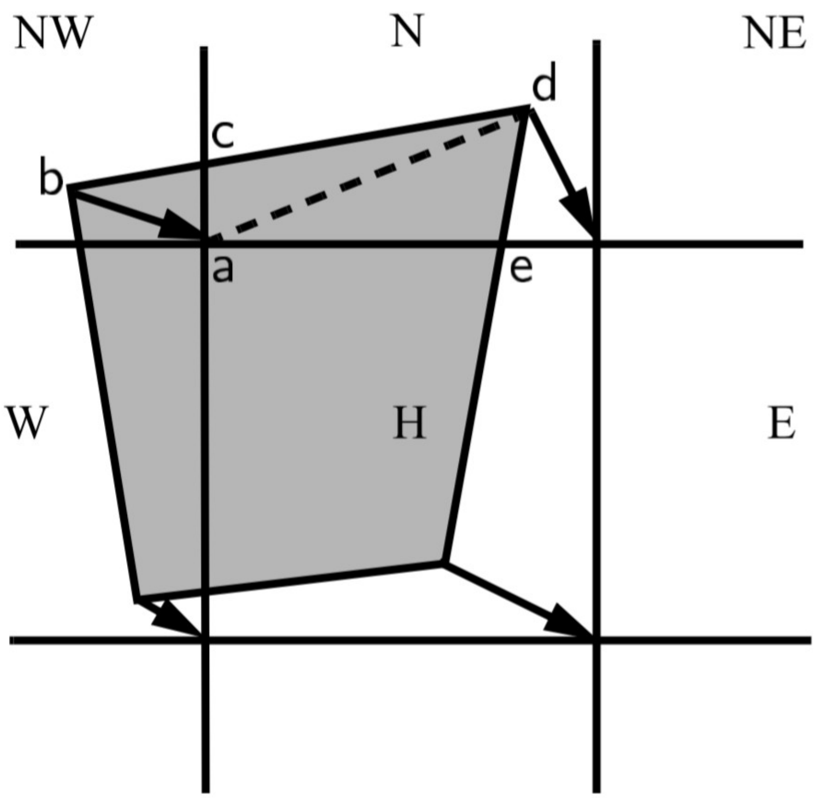


$$a = \sum_i a_i$$

Horizontal Transport

- **Upwind or incremental remapping, latter better for:**
  - Conservation
  - Non-oscillatory
  - Monotonic
  - Second-order accurate
  - Efficient for many tracers

Incremental Remapping



- Compute weights once per timestep
- Use on all tracers
- Some tracers numbered NICELYR* NICECAT

Thermodynamics

- **Three options**
  - Zero-layer of Semtner
  - Bitz and Lipscomb with fixed salinity profile
  - "Mushy" with evolution of salinity profile
- **Temperature-dependent specific heat for brine pockets (options #2 and #3)**

More Thermo

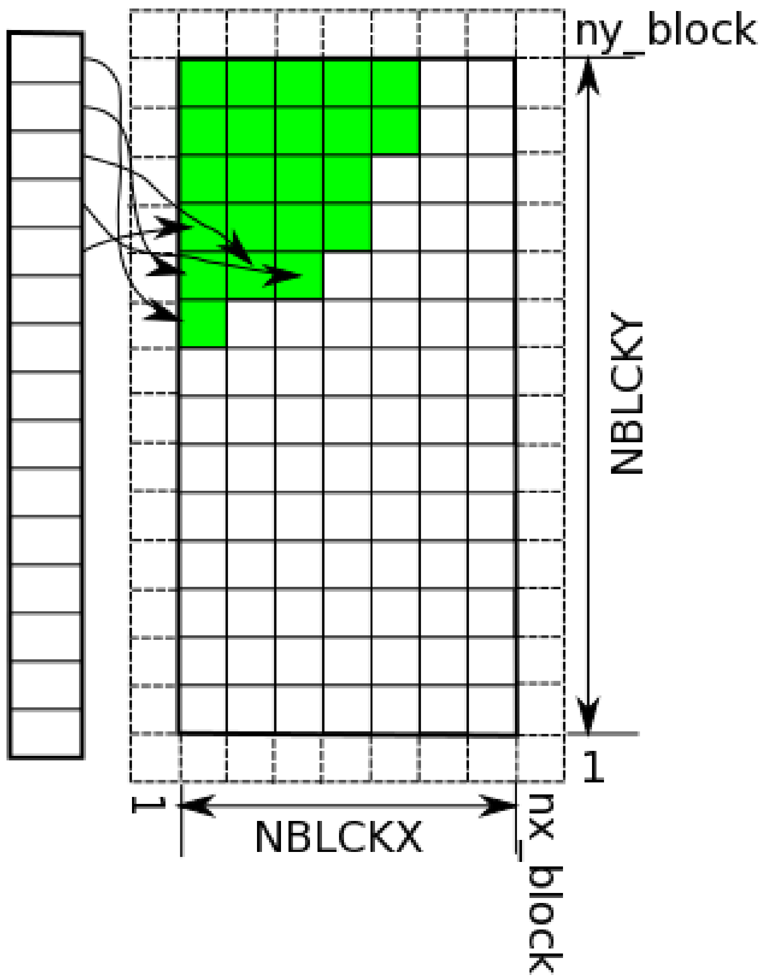
- **Lateral melt**
  - Adjust ice energy and fluxes
  - Assume floe diameter of 300 m
- **Three melt pond options plus default implicit ponds**
  - CESM
  - Topo
  - Level

Boundary Conditions

- **Place away from ice edge**
- **Can specify boundary values with “restore_ice” option**
  - Persistent initial conditions by default
  - Requires “restart_ext” option
- **Unreleased branch BC code?**

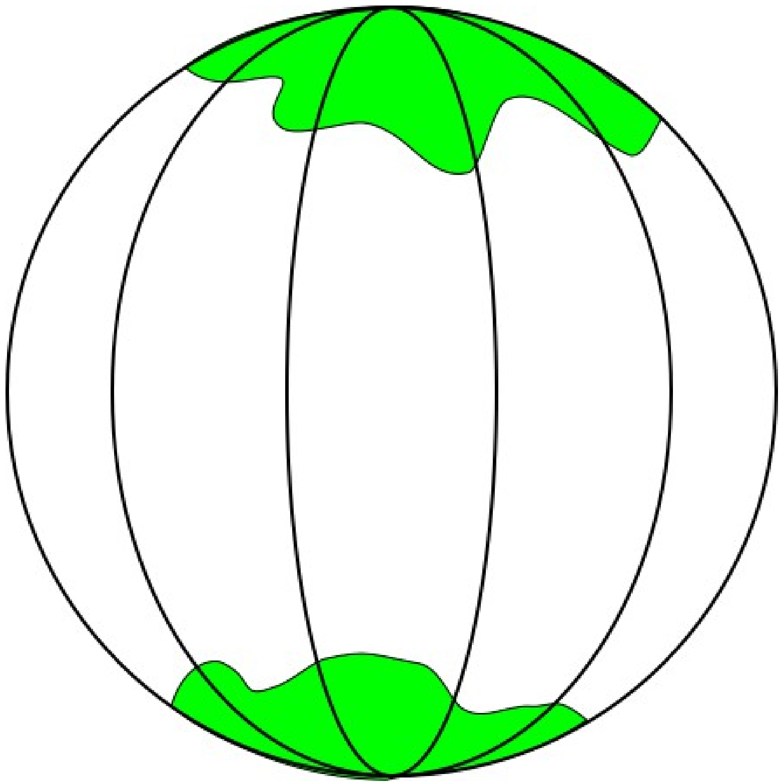
Domain Decomposition

- **Set size of tiles at compile time**
- **All tiles numbered 1 to nx_block, 1 to ny_block (halo of 1)**
- **On each tile, each step, build list of cells with ice to compute over**



Domain Decomposition

- Load-balance by having similar amounts of ice on all tiles
- Tiles on global grids like slices of an orange (or tripole equivalent)



Exchange of Information

- **ROMS to CICE**
  - Atmospheric forcing fields
  - Frazil ice formed/available heat
  - Surface ocean properties
- **CICE to ROMS**
  - Ice concentration
  - Heat, salt and momentum fluxes
- **ROMS must compute bulk fluxes over water and merge with fluxes from CICE**

CICE Compile-time Options

- SITE – points to config in CICE's bld directory
- SYSTEM_USERDIR – where to put object files
- SRCDIR – location of CICE code
- RES – name of domain
- GRID – dimensions of horizontal grid
- NTASK – number of MPI processes

Continued…

- **BLCKX – size of tiles in i-direction**
- **BLCKY – size of tiles in j-direction**
- **NICELYR – number of vertical ice layers**
- **NSNWLYR – number of vertical snow layers**
- **NICECAT – number of ice thickness categories**

Continued…

- Tracer options
- BGC options
- IO_TYPE – none, pio or netcdf
- THRD – for OpenMP

ice_in

- **Run-time switches for many things (namelists)**
  - Time variables
  - Grid setup
  - Restart
  - Dynamic and thermodynamic choices (EVP vs EAP, melt ponds, etc)
  - Output control
- **NPROCS must match compiled-in value!**

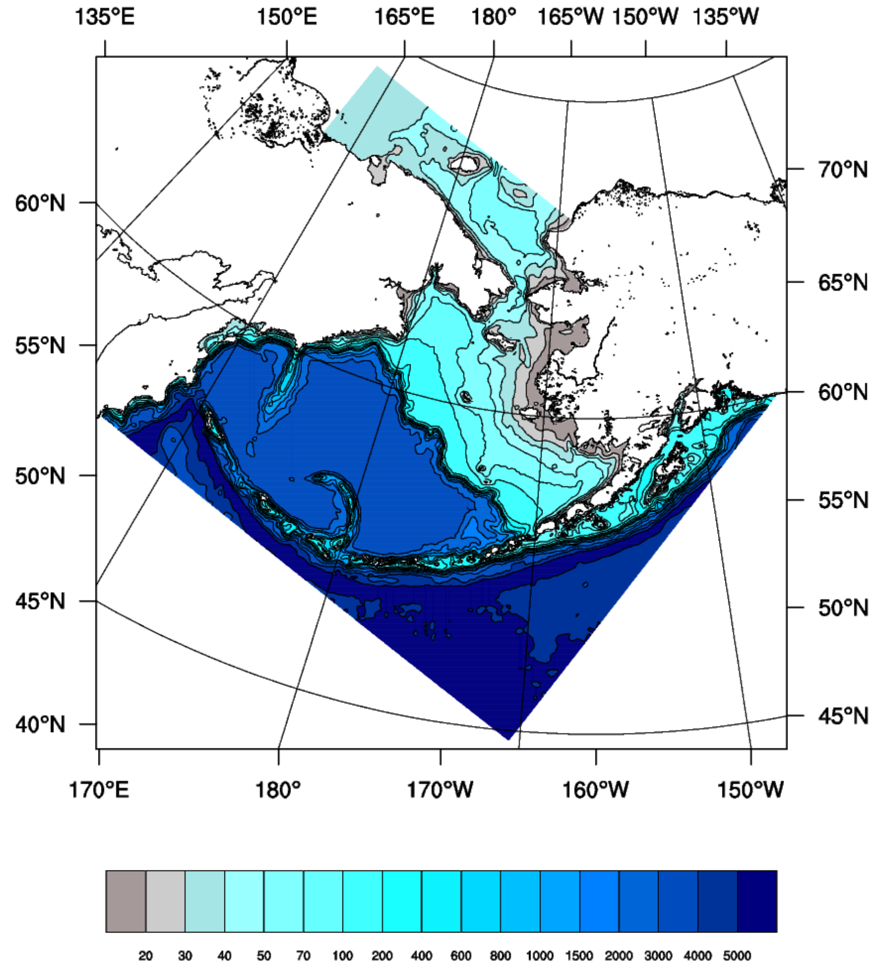
Model Domains with Sea Ice

Examples

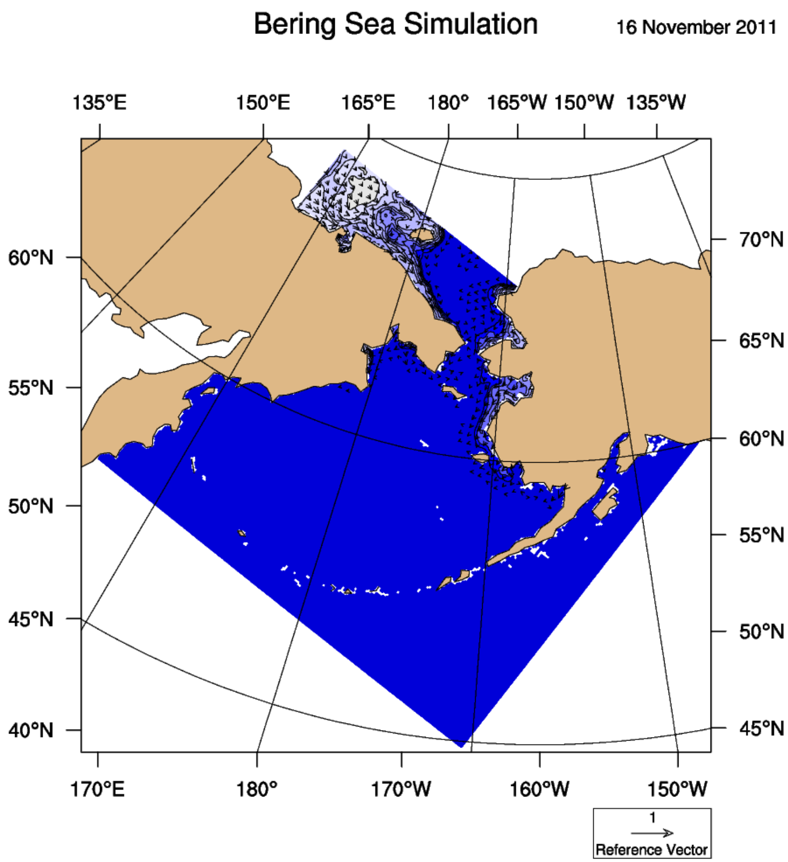
- **Bering Sea**
  - 10 km WRF grid
- **Arctic2**
  - Also known as PAROMS
- **Beaufort Sea**
  - Offline nesting (Budgell ice)

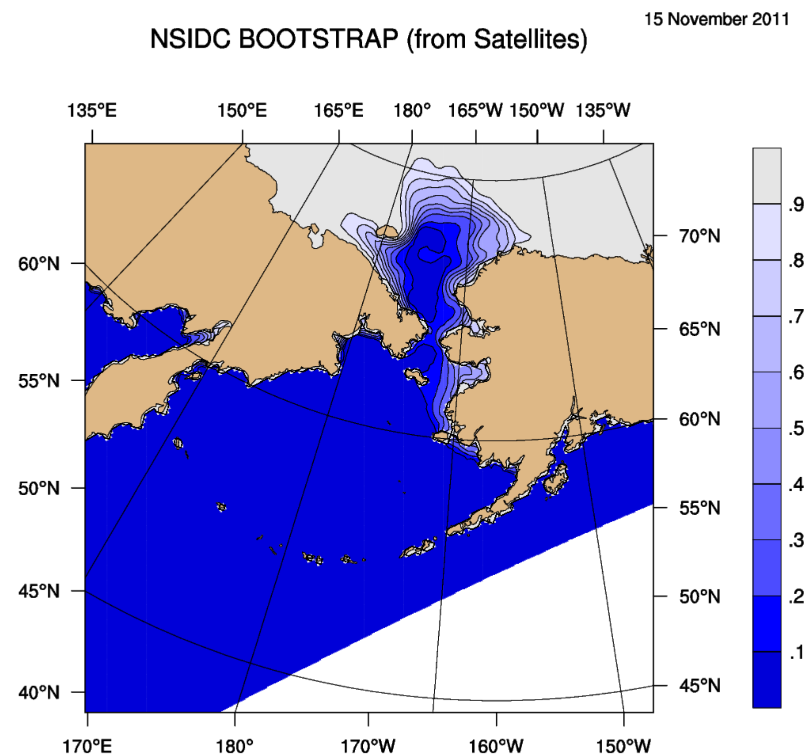
Bering Sea Test

- Start in September with no ice
- Watch ice grow and retreat over a year
- WRF-ROMS for Nov 2011 storm (future plan)

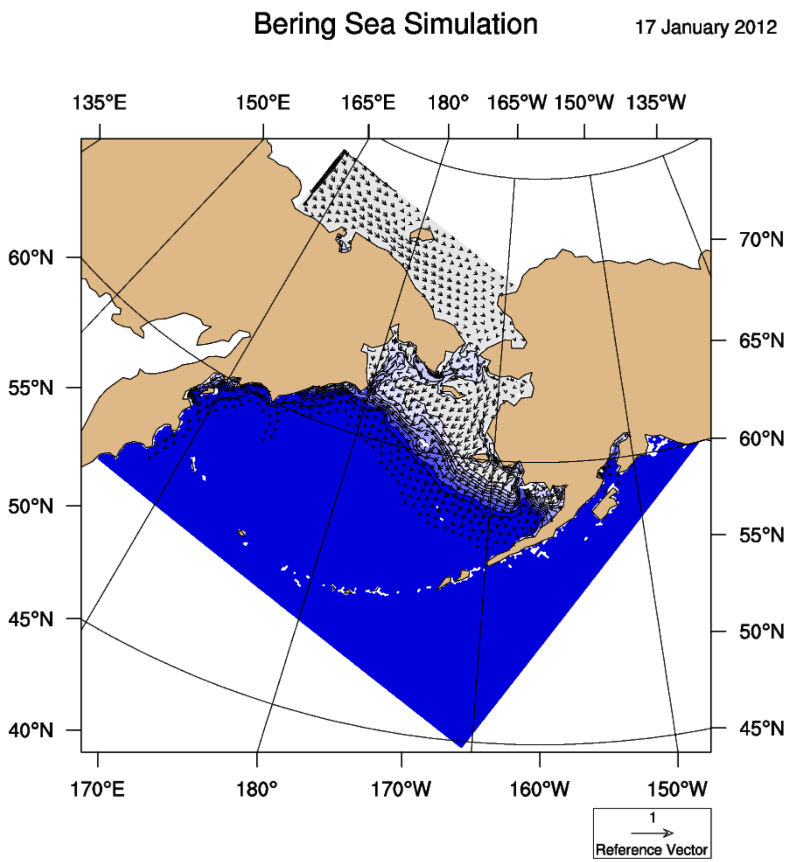


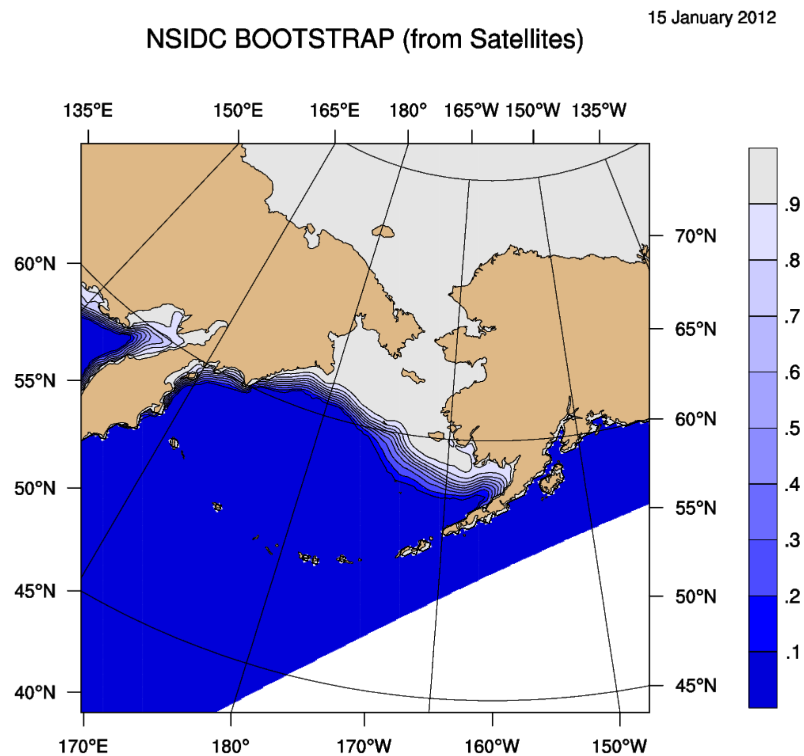
November 2011



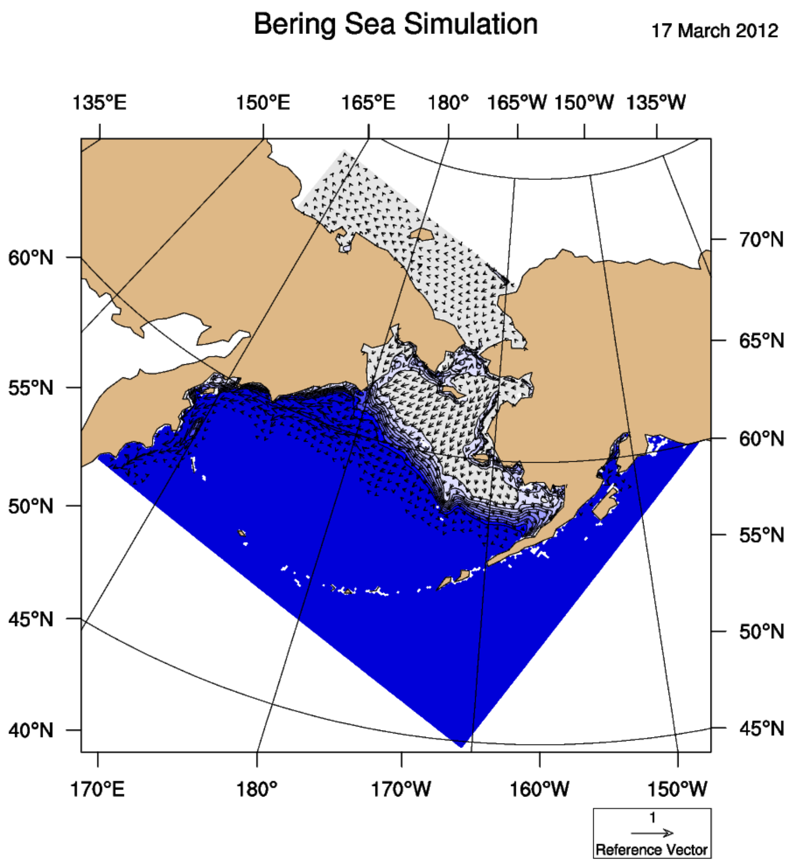


January 2012





March 2012


Bering Sea Simulation
17 March 2012
135°E
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165°E
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135°W
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45°N
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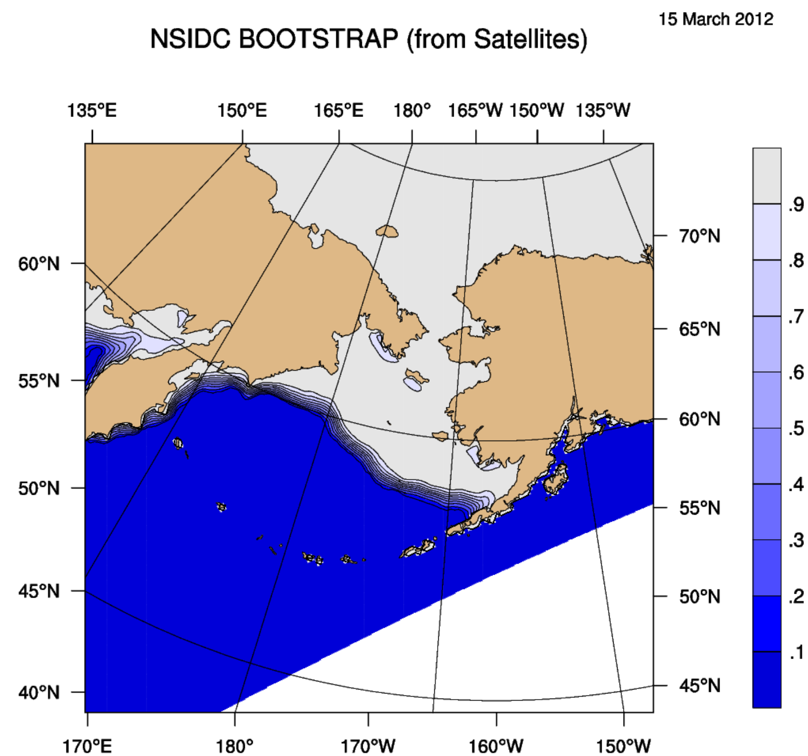
Reference Vector


15 March 2012
NSIDC BOOTSTRAP (from Satellites)
135°E
150°E
165°E
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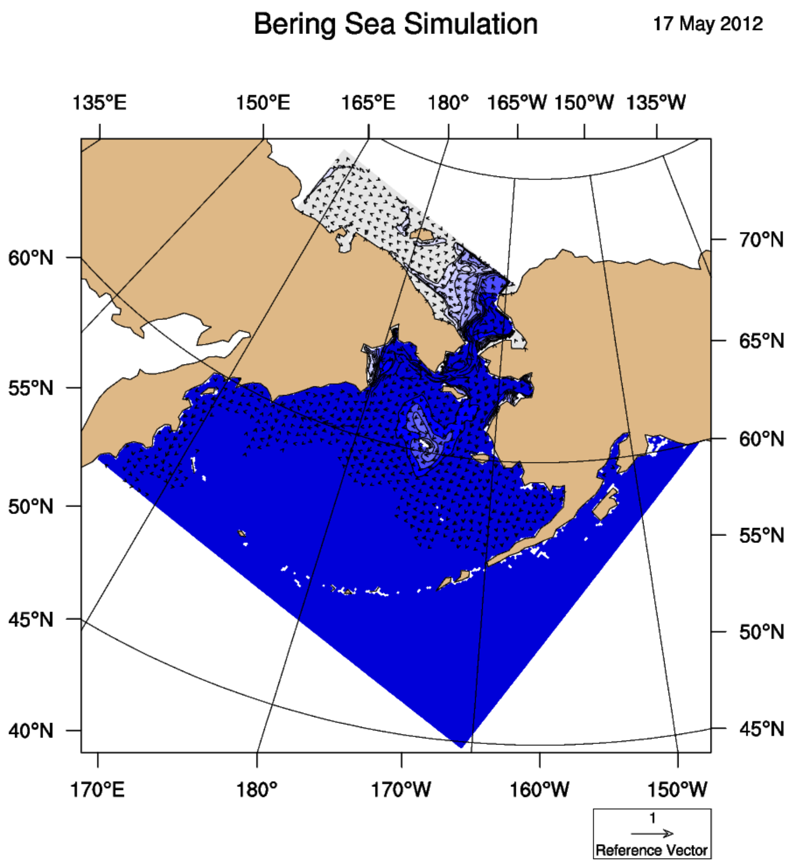
May 2012



Bering Sea Simulation
17 May 2012
135°E
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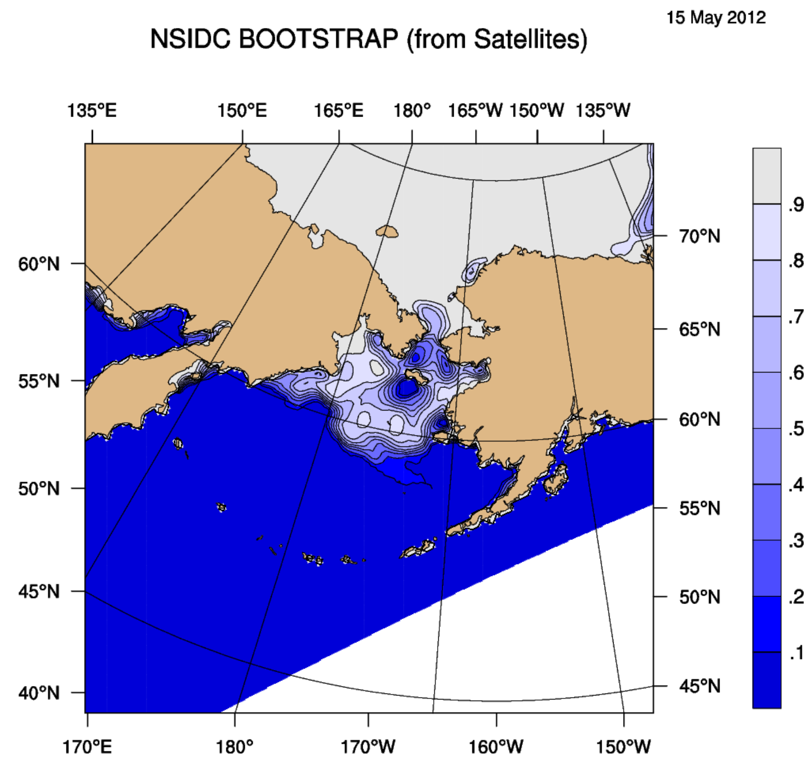
Reference Vector



15 May 2012
NSIDC BOOTSTRAP (from Satellites)
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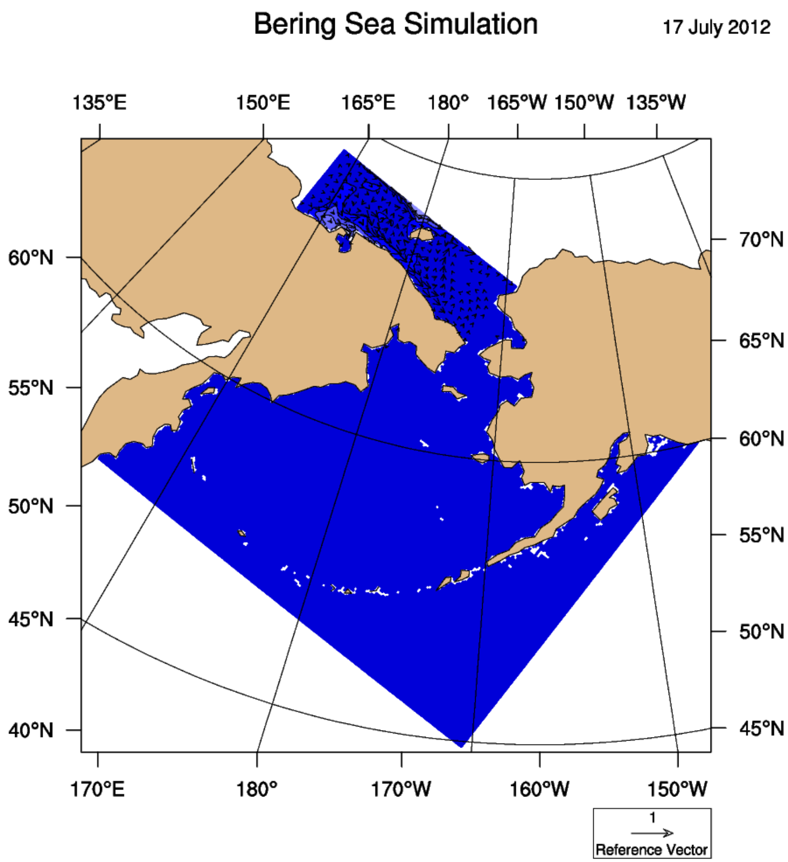
July 2012


Bering Sea Simulation
17 July 2012
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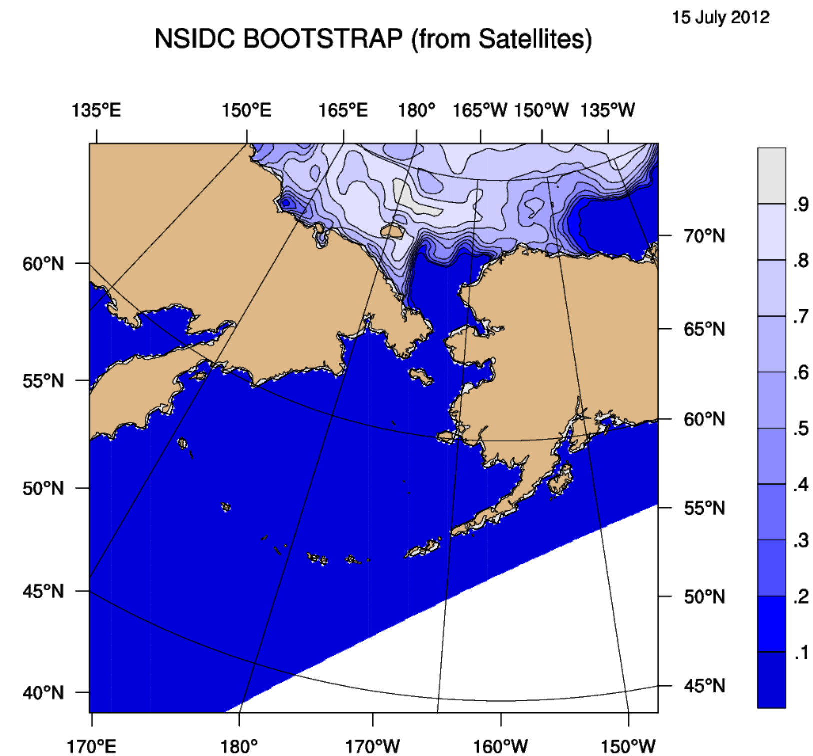
Reference Vector


15 July 2012
NSIDC BOOTSTRAP (from Satellites)
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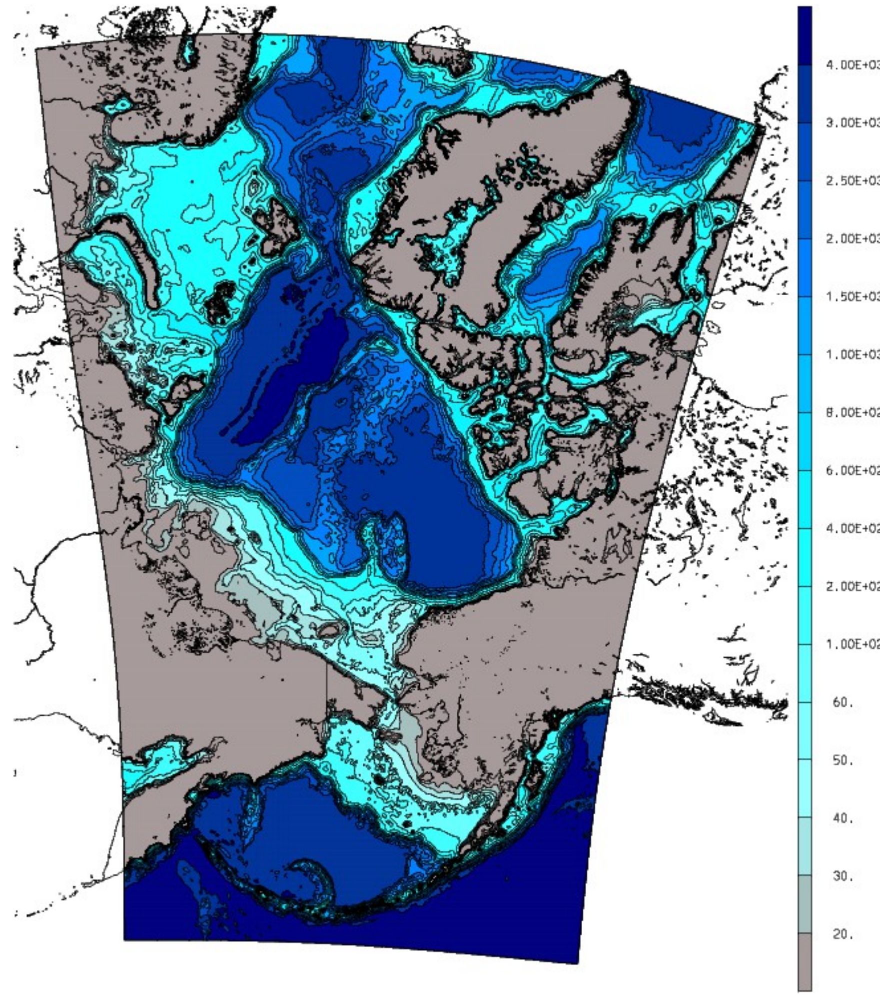
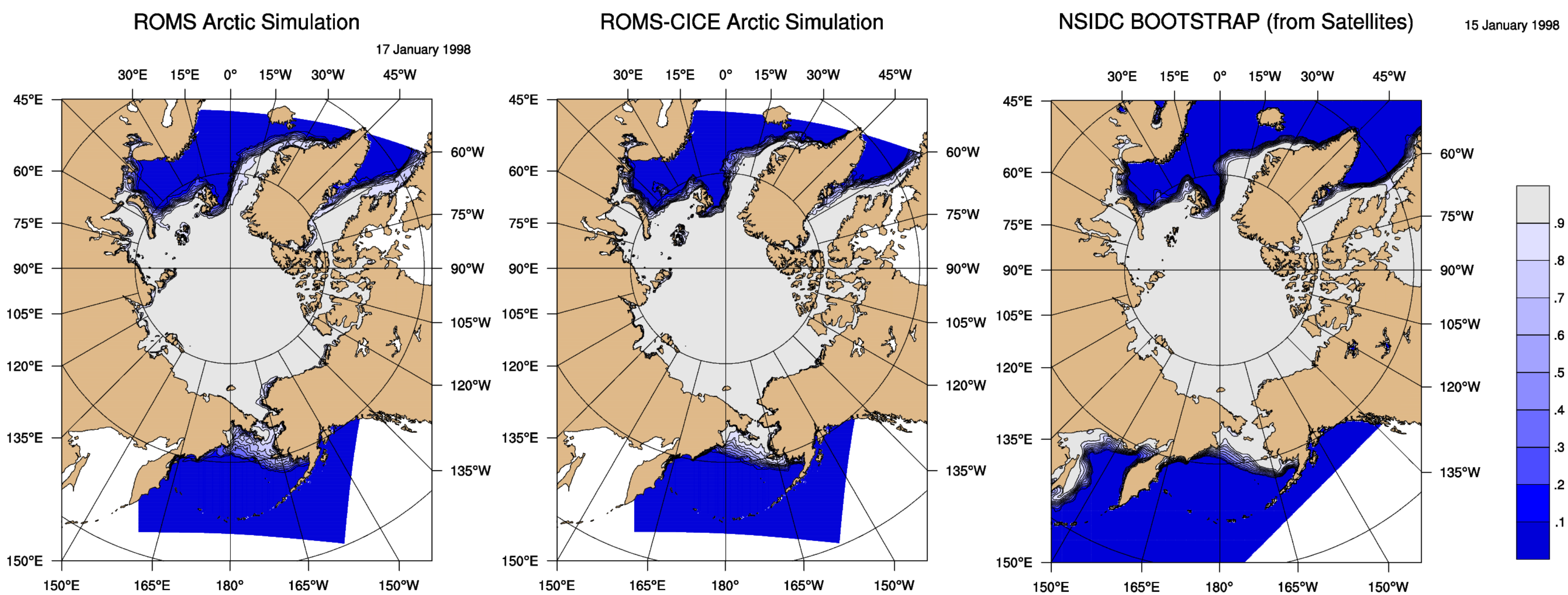
PAROMS

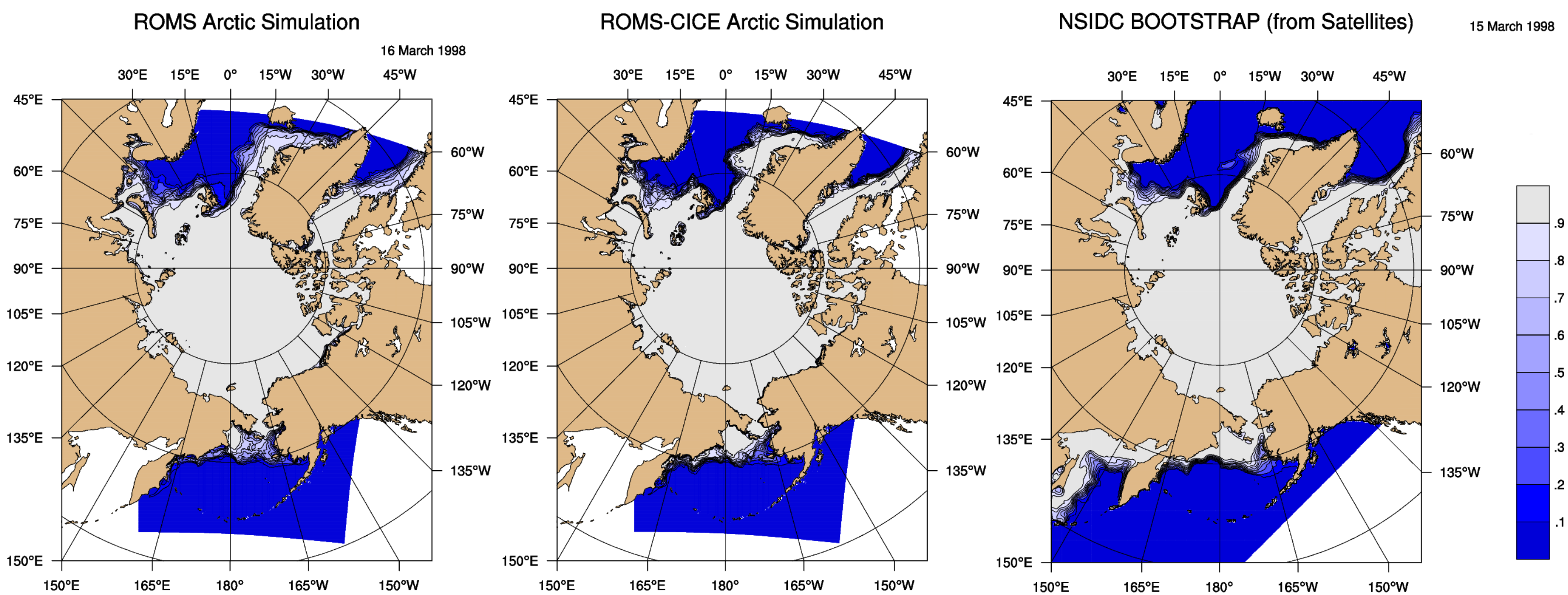
- **MERRA forcing**
- **Fresh water**
  - ARDAT in Arctic
  - Dai et al. elsewhere
- **GLORYS IC**
- **SODA BCs (HYCOM in other years)**



January 1998



March 1998


ROMS Arctic Simulation
16 March 1998
ROMS-CICE Arctic Simulation
NSIDC BOOTSTRAP (from Satellites)
15 March 1998
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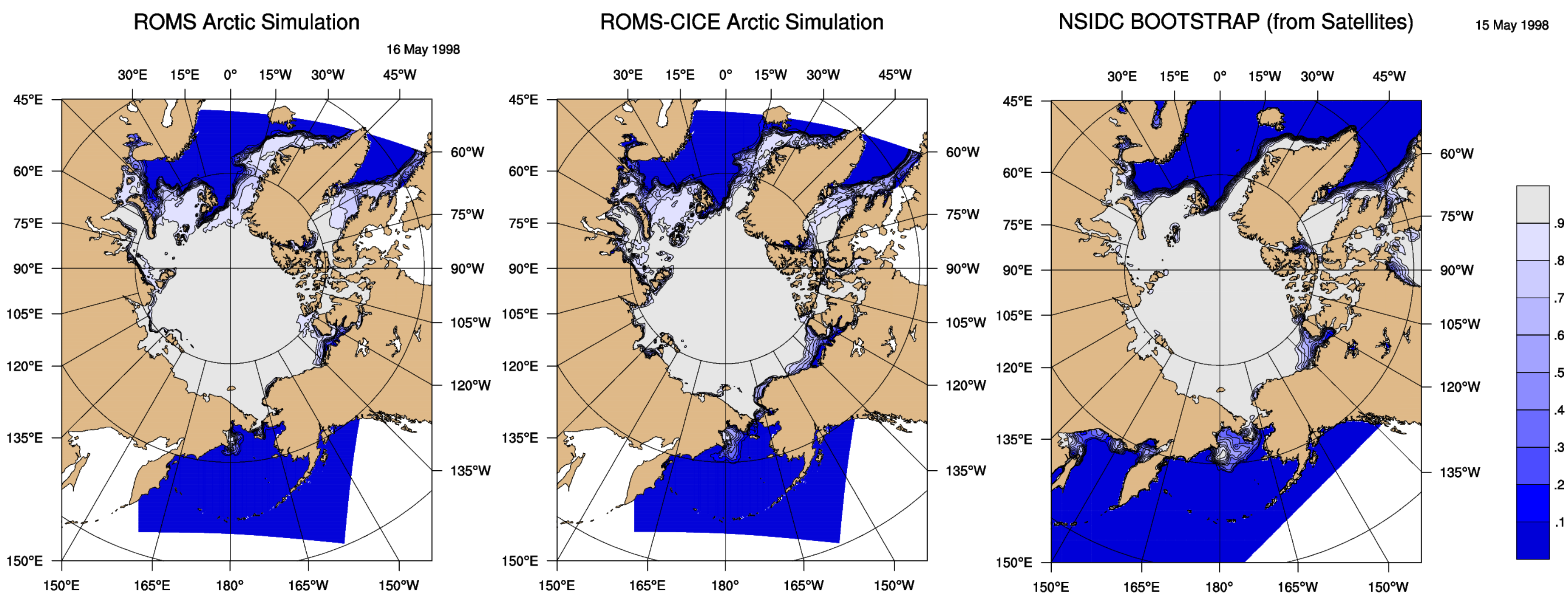
May 1998



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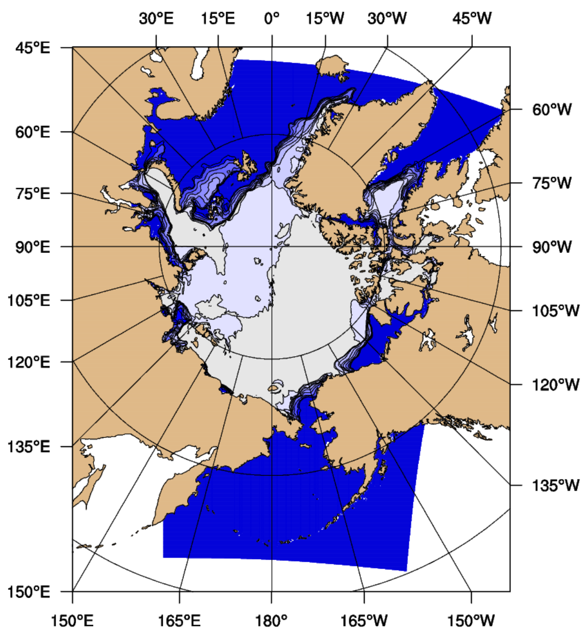
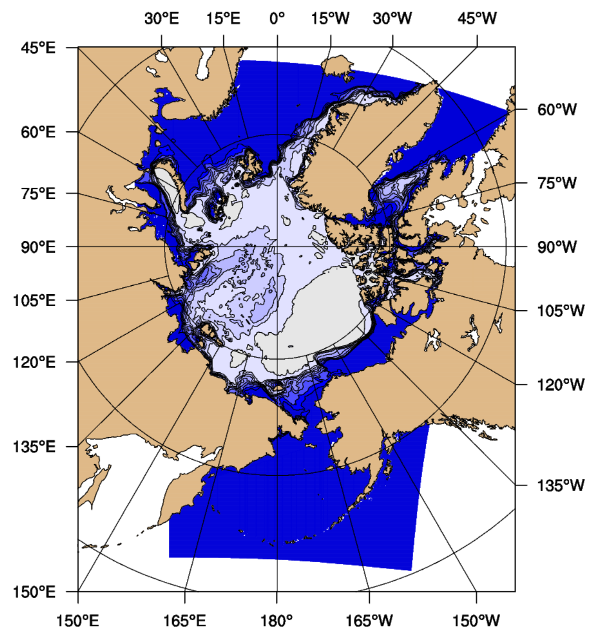
July 1998

ROMS Arctic Simulation

16 July 1998

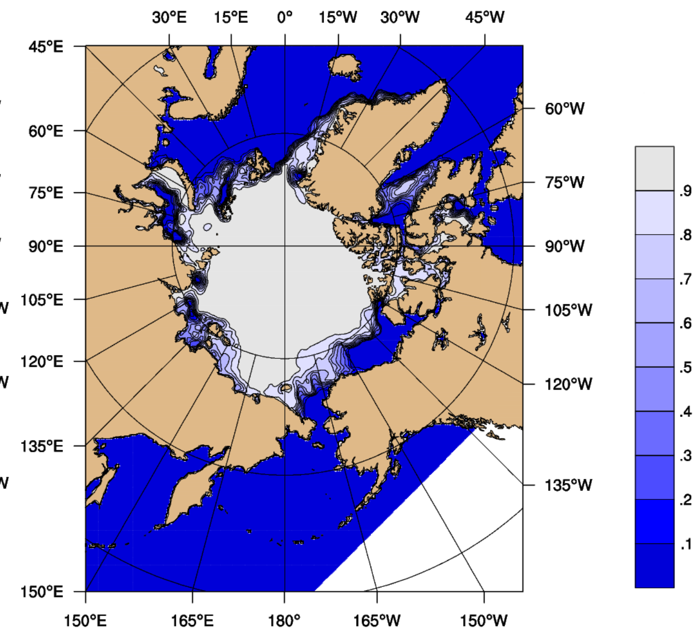


ROMS-CICE Arctic Simulation

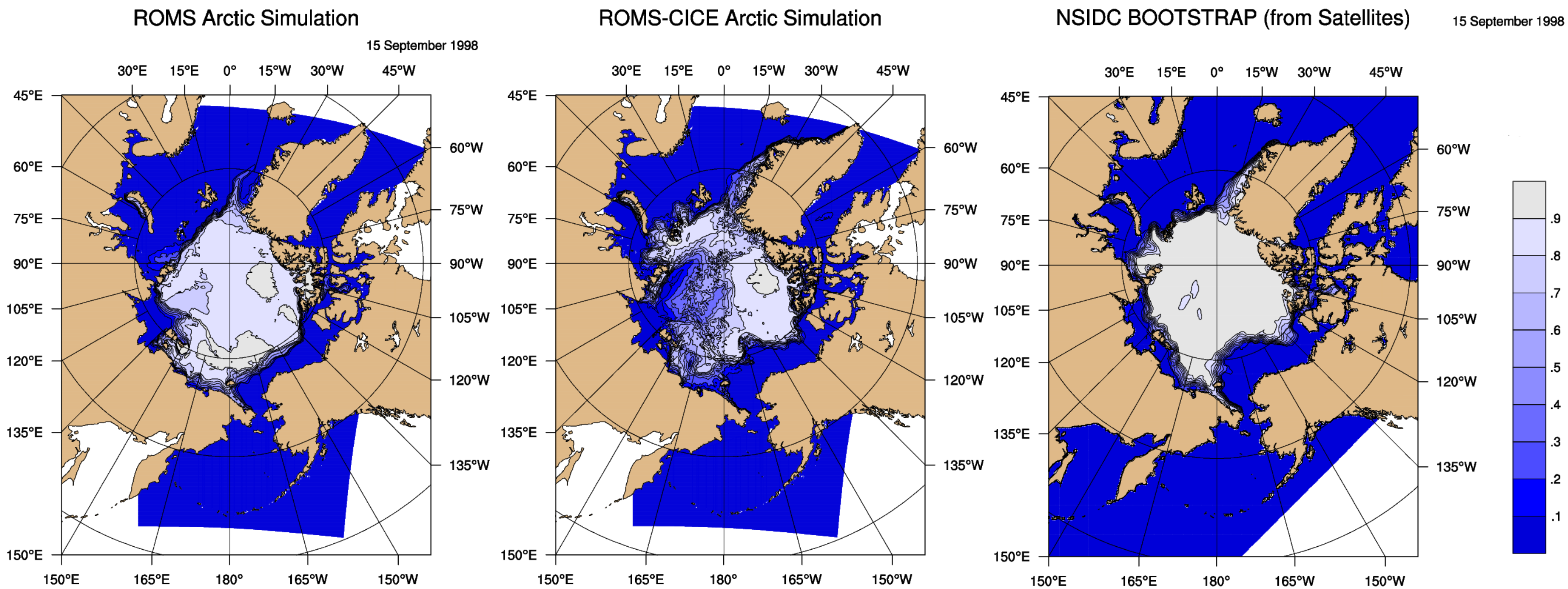


NSIDC BOOTSTRAP (from Satellites)

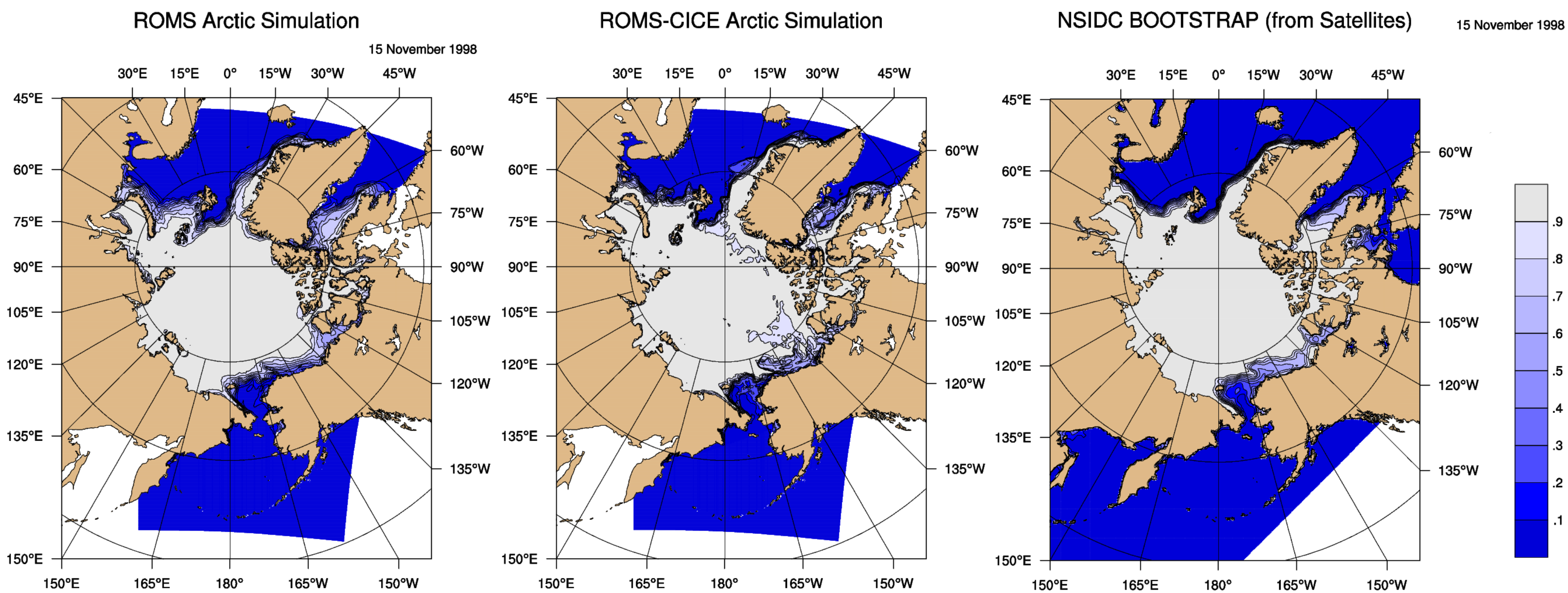
15 July 1998



September 1998

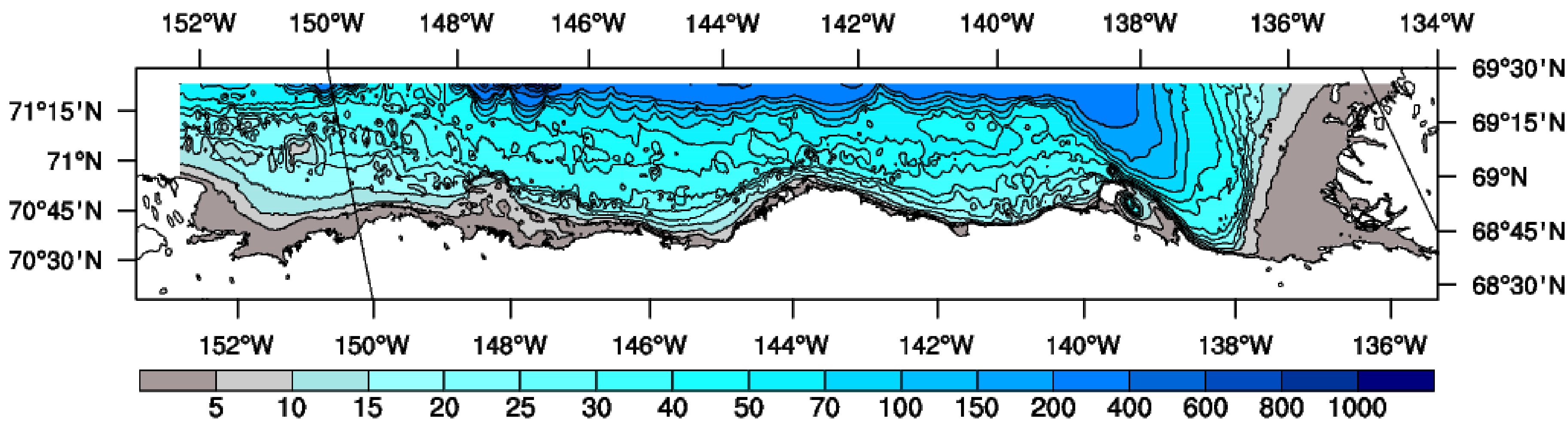


November 1998



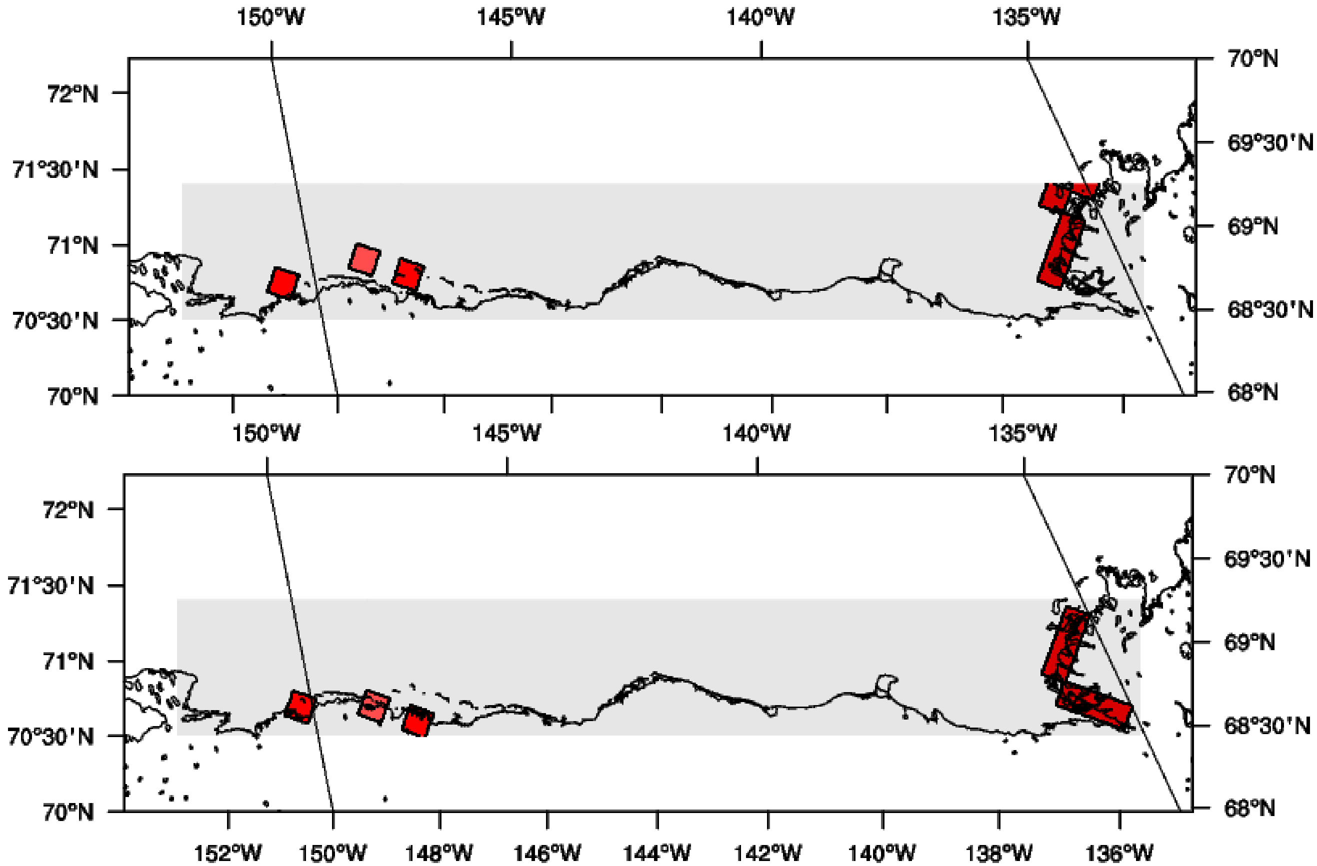
Beaufort Sea

- **BOEM-funded project in coastal Beaufort Sea**
  - Flow near barrier islands
  - Flow under landfast ice
  - Budgell ice, offline nesting

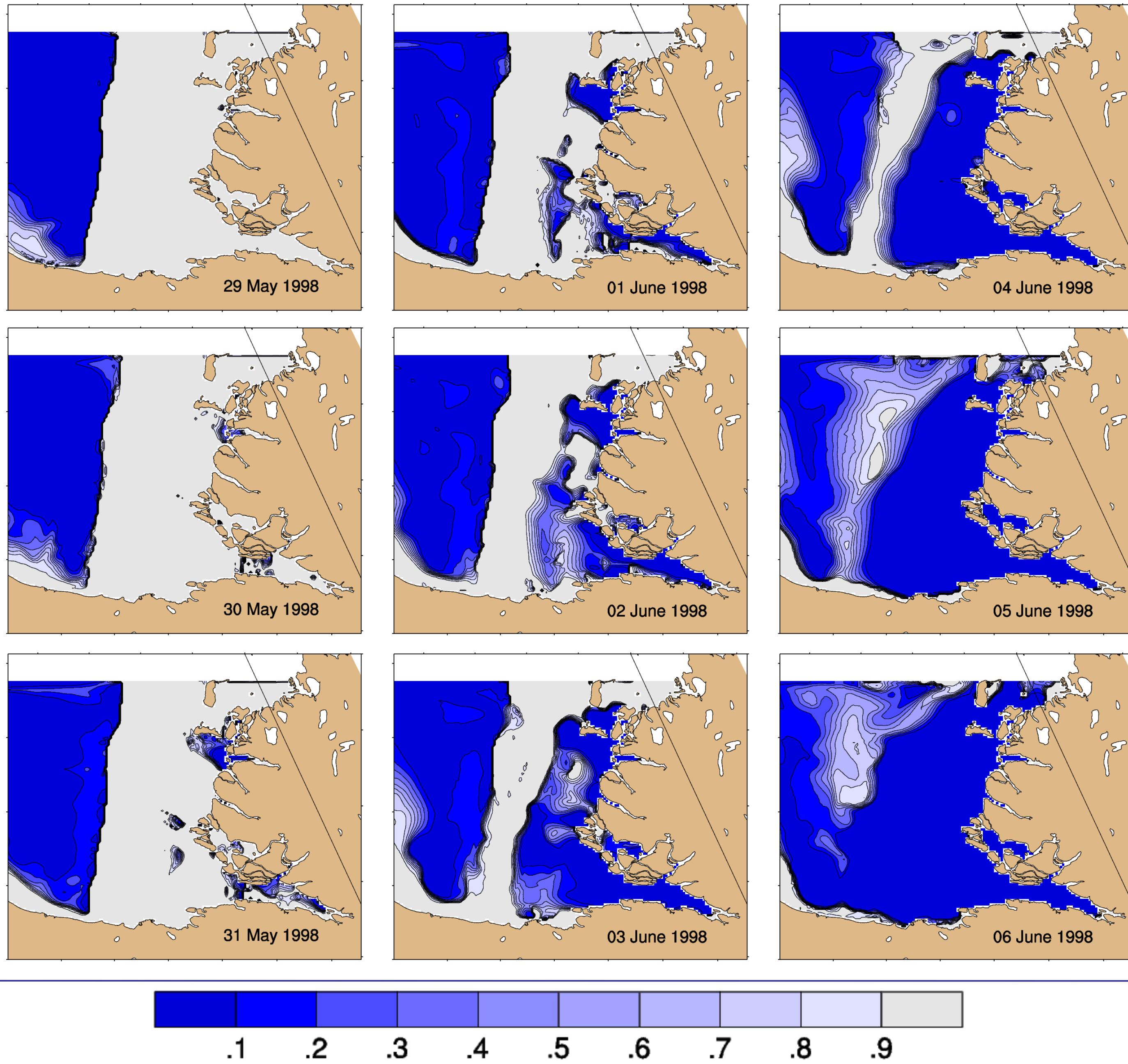


Arctic River (ARDAT) Climatology

- Adjust locations
- Map to ROMS grid
- Move to ROMS coastline
- Convert to river file



Sea Ice Concentration in MacKenzie Delta



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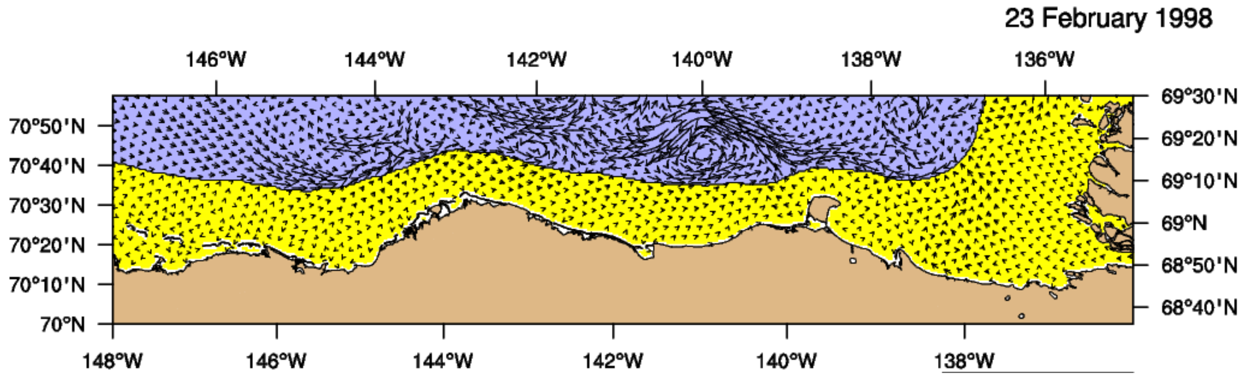
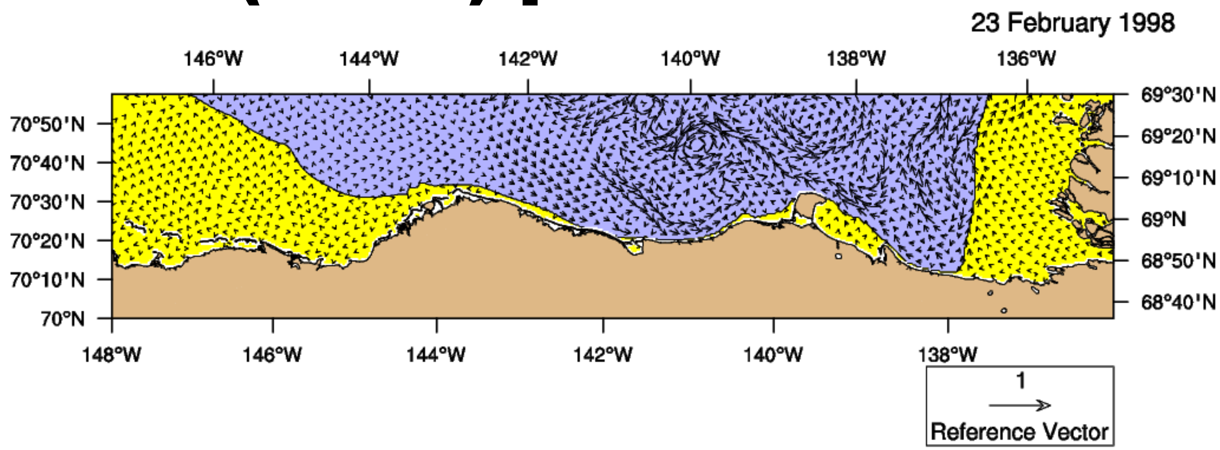
Landfast ice

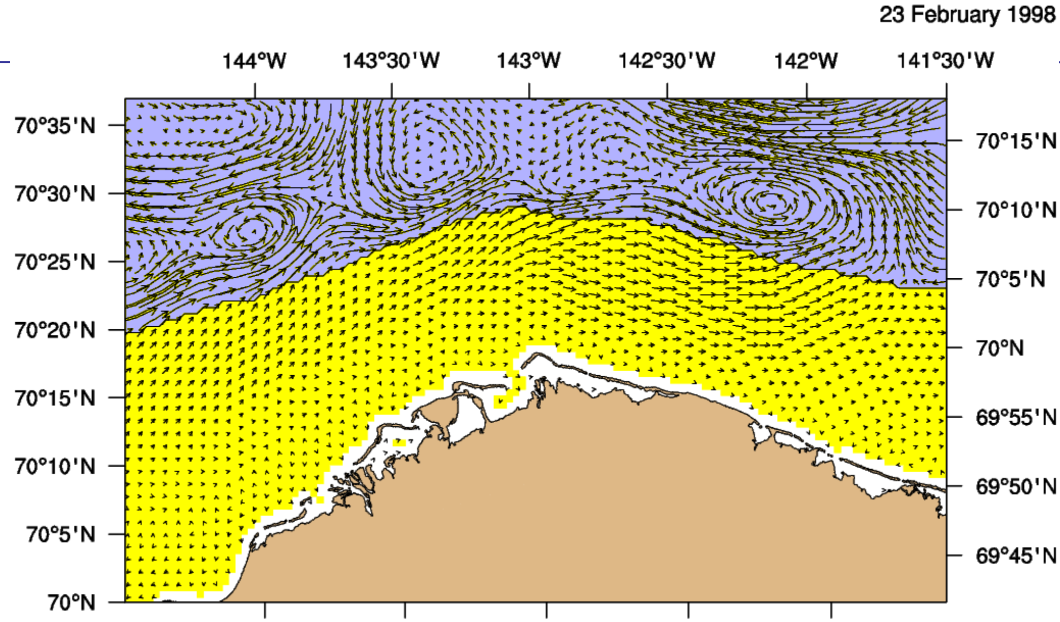
Clamp to Mahoney climatology

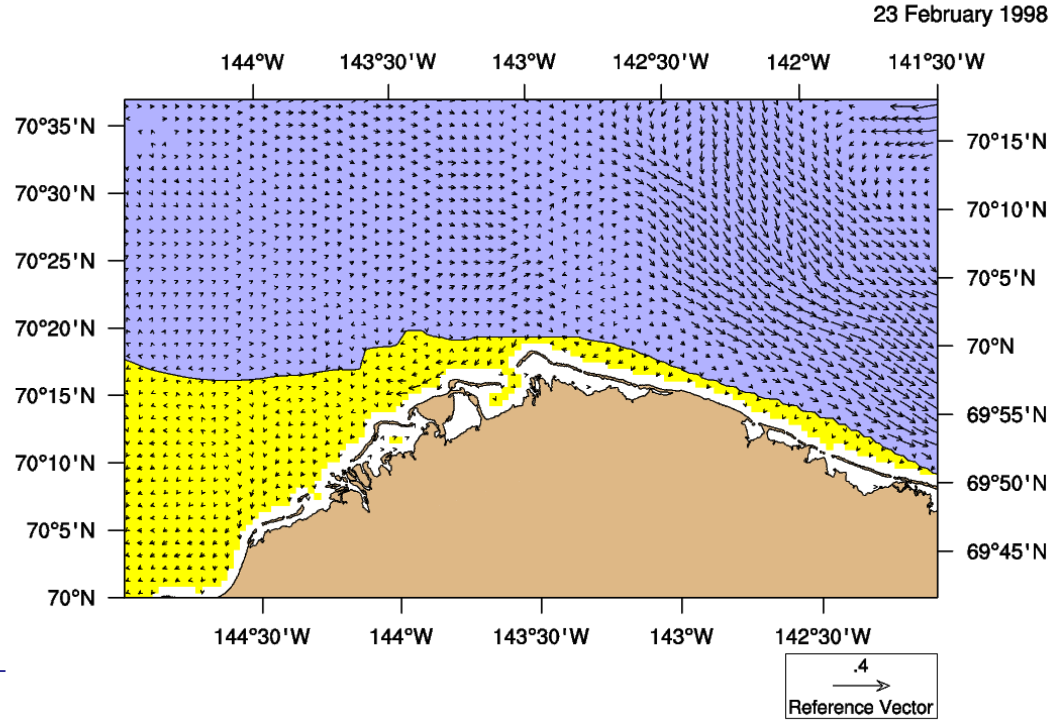


Lemieux (2015) parameterization



Zooming in





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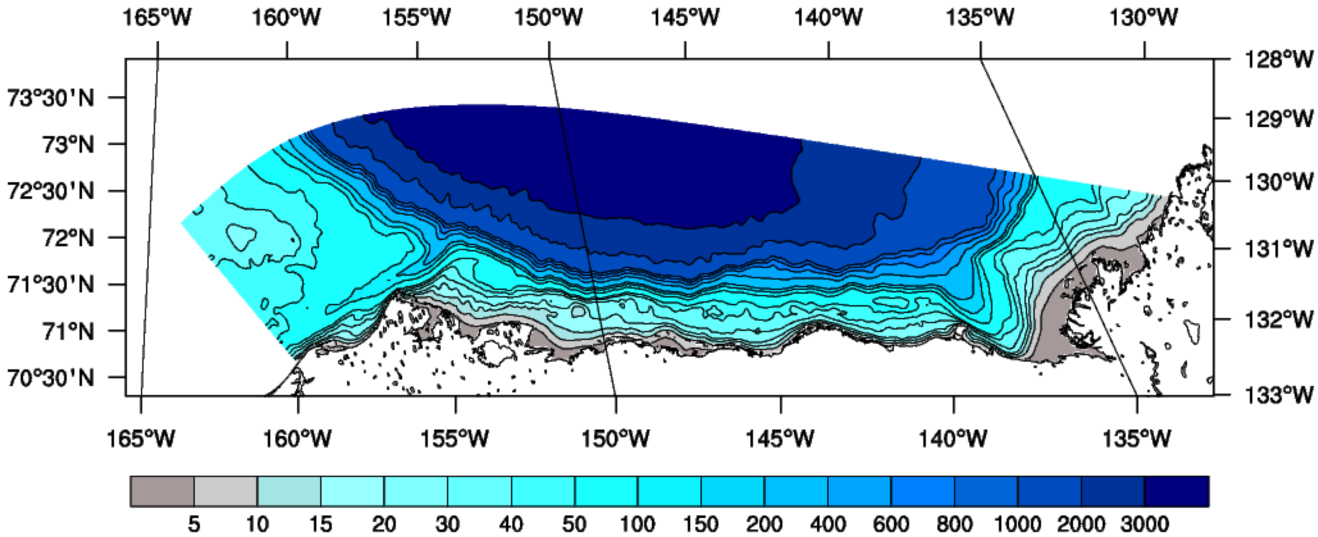
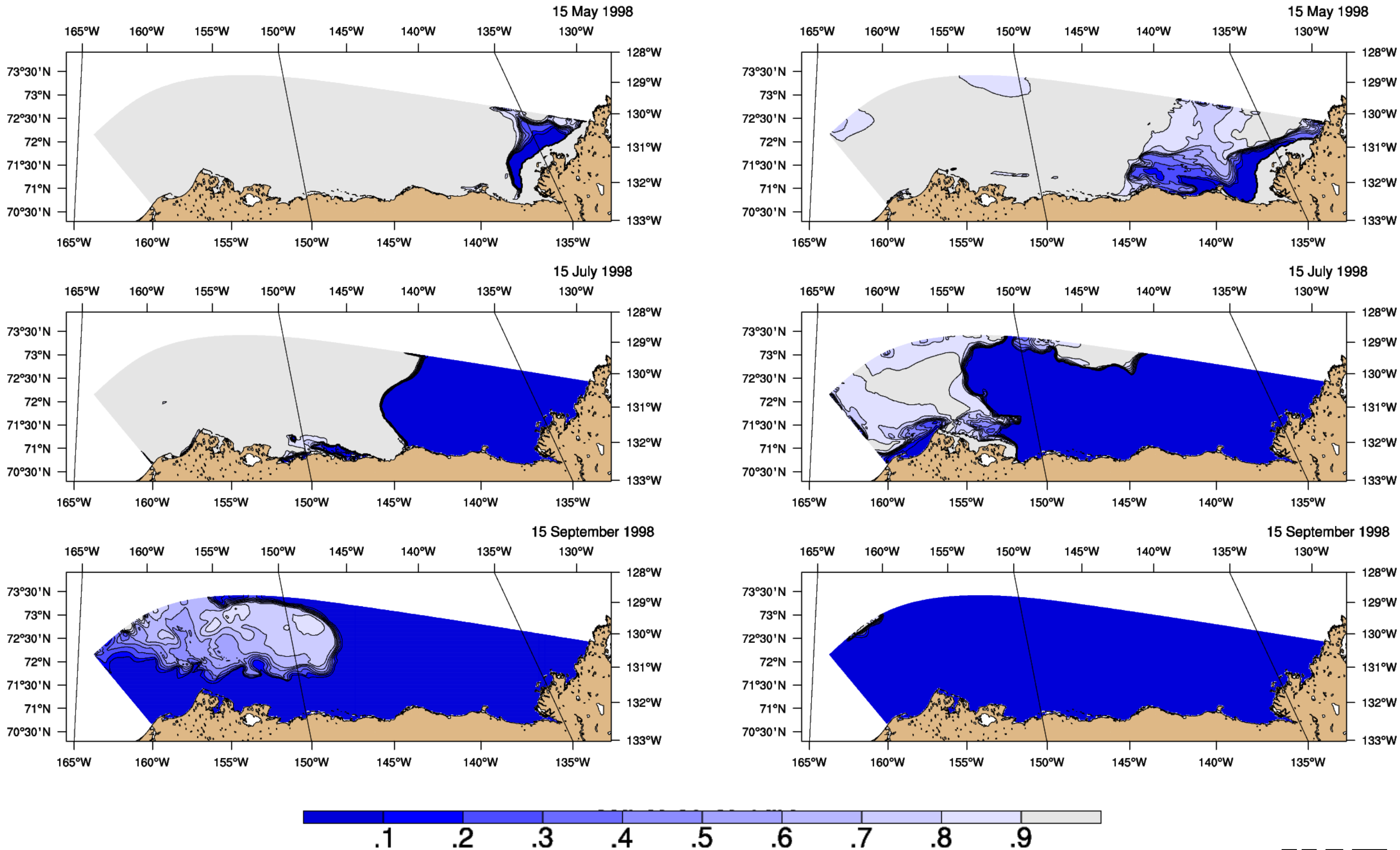
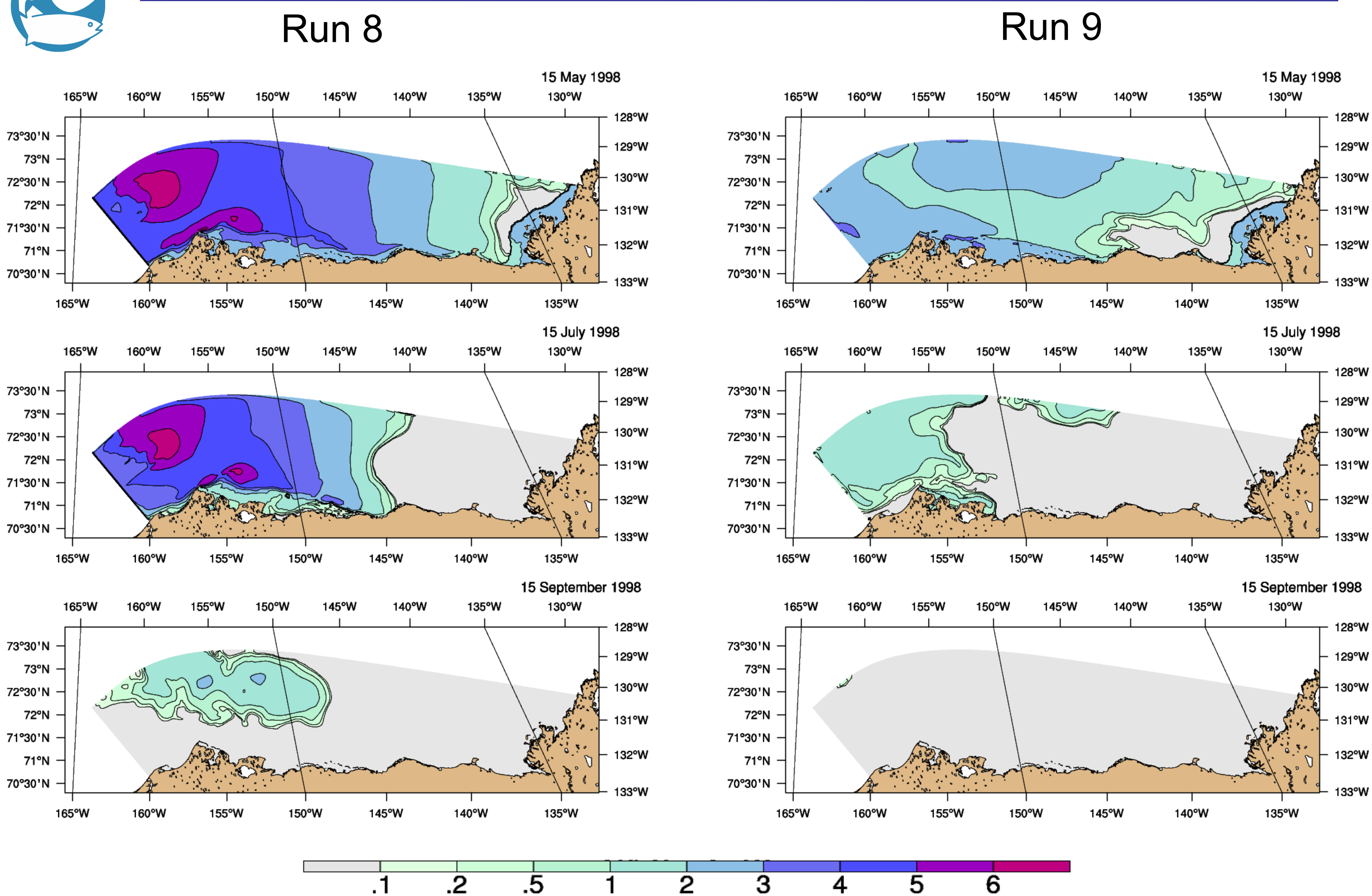
Beaufort #2

- 3 km resolution



Run 8 Run 9


15 May 1998
15 July 1998
15 September 1998
165°W 160°W 155°W 150°W 145°W 140°W 135°W 130°W
128°W 129°W 130°W 131°W 132°W 133°W
73°30'N 73°N 72°30'N 72°N 71°30'N 71°N 70°30'N
165°W 160°W 155°W 150°W 145°W 140°W 135°W
.1 .2 .3 .4 .5 .6 .7 .8 .9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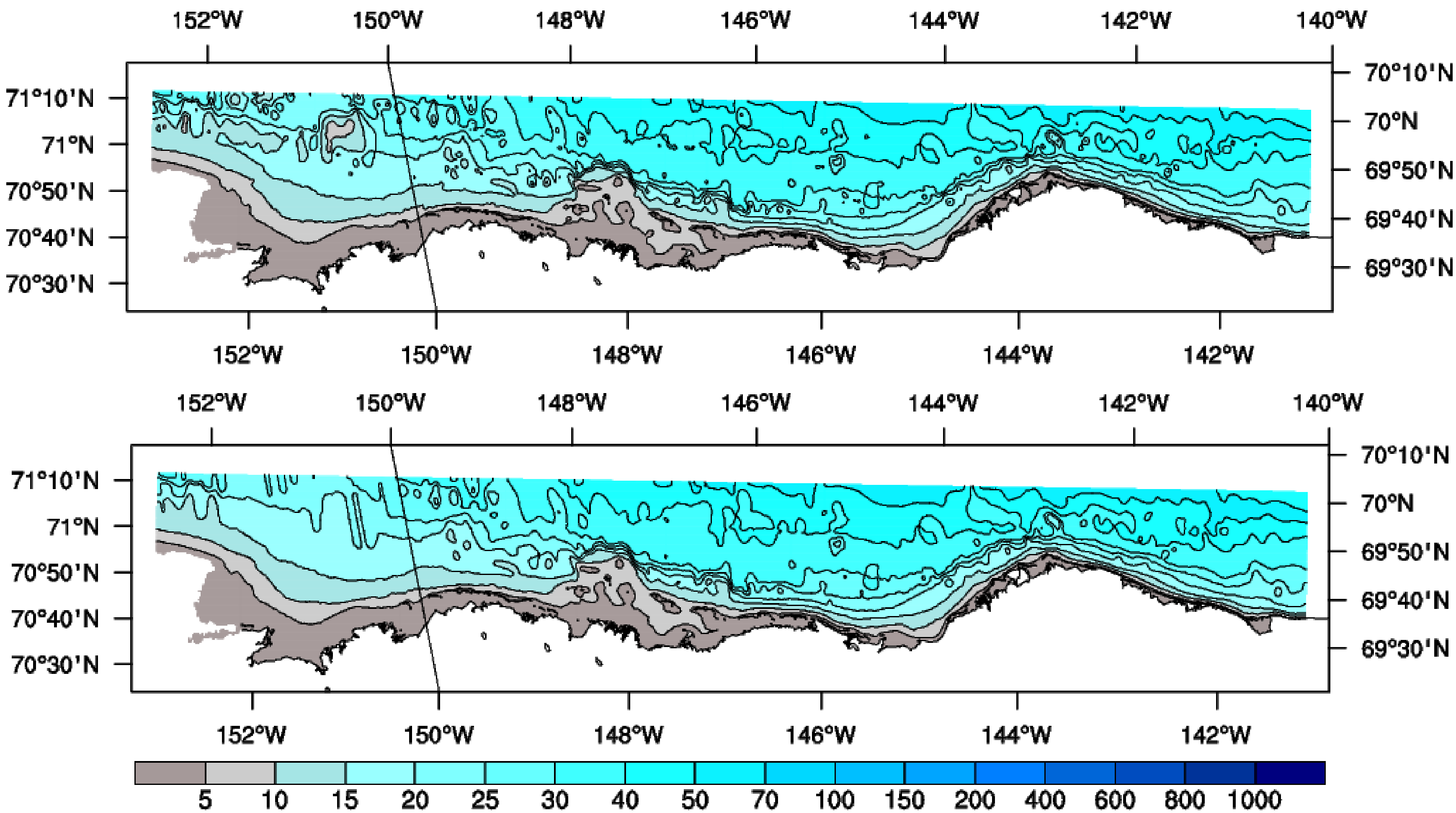
72°30'N
72°N
71°30'N
71°N
70°30'N
.1
.2
.5
1
2
3
4
5
6

Beaufort #3

- 500 m resolution



Boundary Fussing

- **Boundary condition with external values**
  - aice, hice, hsn
  - sigma
- **Nudging band**
- **Turn off landfast ice in nudging band**
- **Bathymetry**

Learn More

- Budgell ice in ROMS manual
- CICE comes with very complete manual in doc directory
- Many relevant papers in doc/PDF directory

Random Tips

- **Circumpolar considerations**
  - GLOBAL_PERIODIC
  - grid_coords.F (floats, stations)
- **Tell CICE the truth about the date**
  - Albedo
  - Output filenames
- **Python scripts to make CICE (POP) grid files from ROMS grid files**
  - Fake coupler different from metroms

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Future Plans

Ongoing Efforts

- **PolarCOAWST group activities**
  - With WRF
  - With ice shelves
- **CICE Consortium**
  - Continue improvements to CICE
- **Hernan's plans?**
- **Biogeochemistry**
- **SIS2**

SIS2 (Hallberg, Winton, Bushuk and Shao)

- **Arakawa C-grid**
- **Embedded ice (instead of floating on top of ocean)**
  - Solves an instability
  - Needed for icebergs too
- **Conservation of enthalpy, mass, salt**
- **Does the bulk flux computations everywhere**
- **Code on github, including test cases**