Toward Eddy-Resolving Models of the Arctic Ocean

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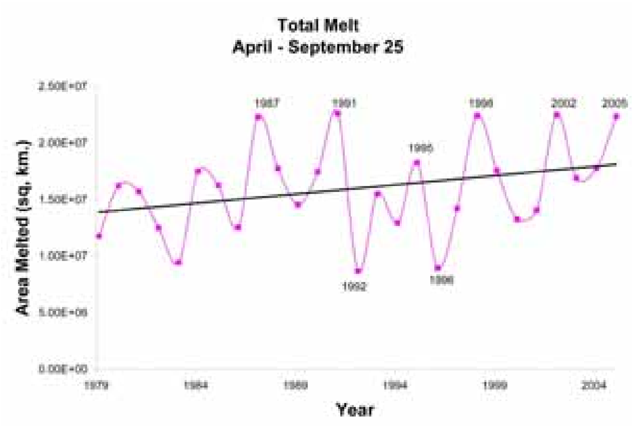
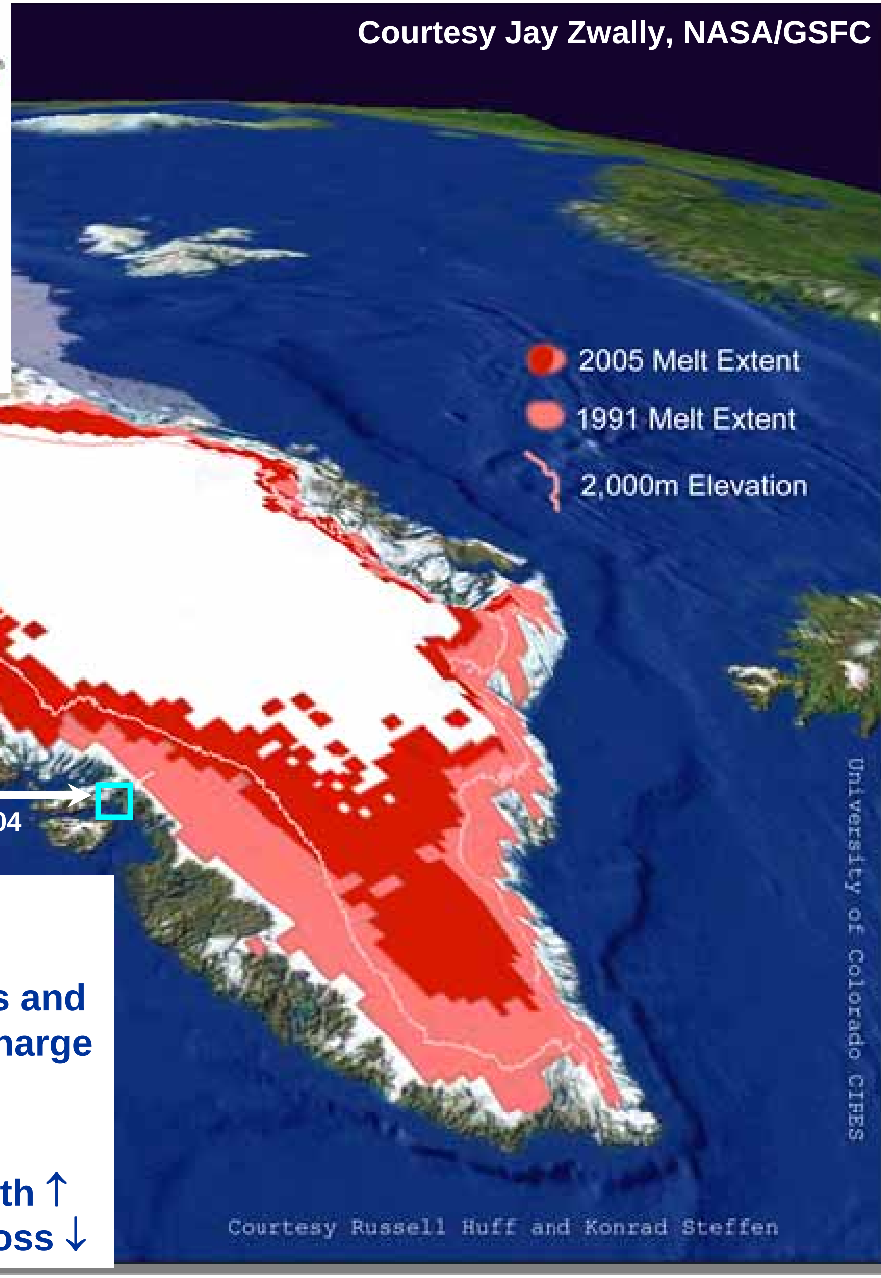
Outline

- **Why Arctic matters?**
- **Why we need eddy-resolving models in the Arctic**
- **Regional Arctic Climate Model project**
- **Conclusions**

> *"A linear increase in heat in the Arctic Ocean will result in a non-linear, and accelerating, loss of sea ice."*
>
> Norbert Untersteiner, Professor Emeritus,
> University of Washington, July 2006

Greenland Ice sheet Melt Extent 2005 – another record melt year

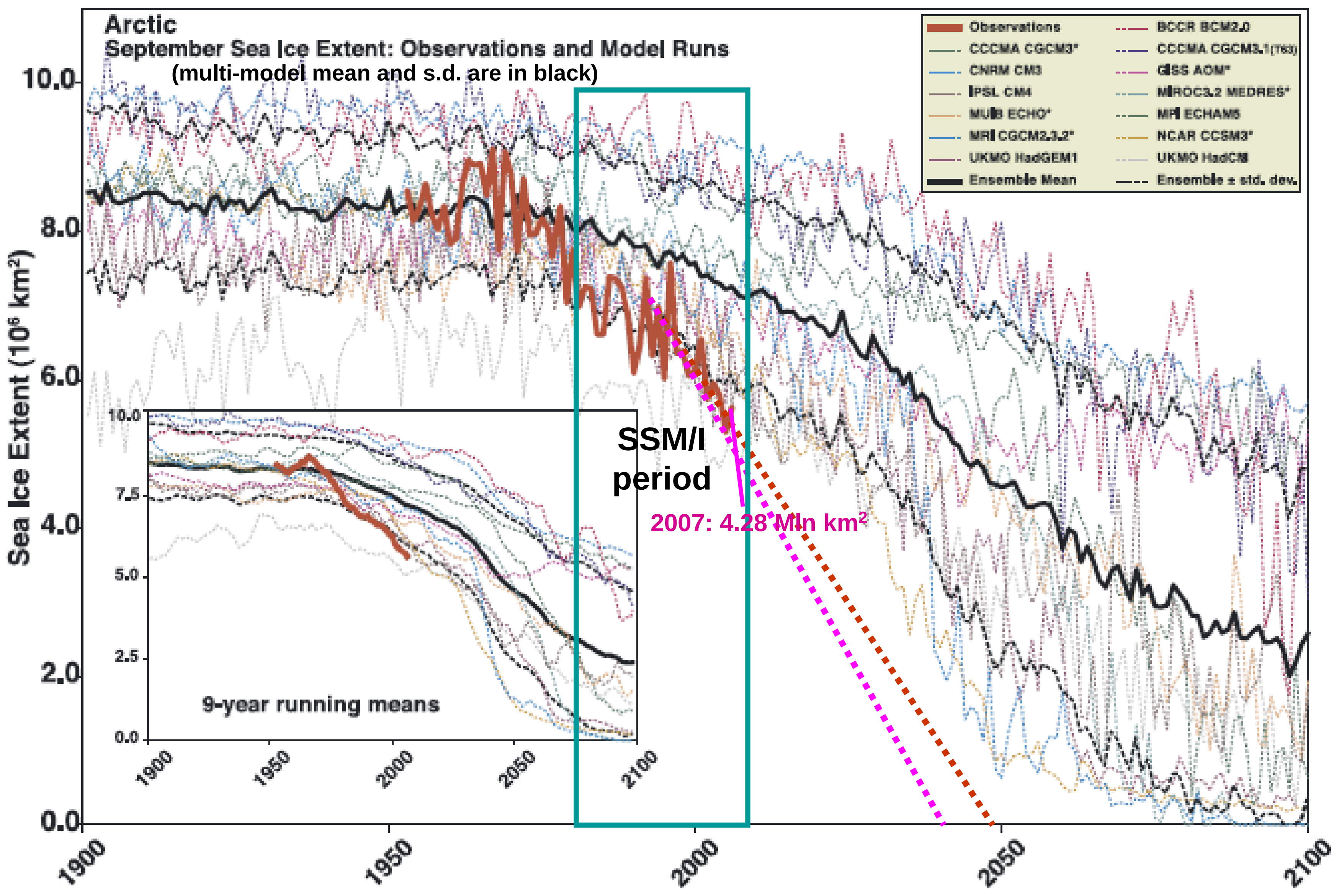




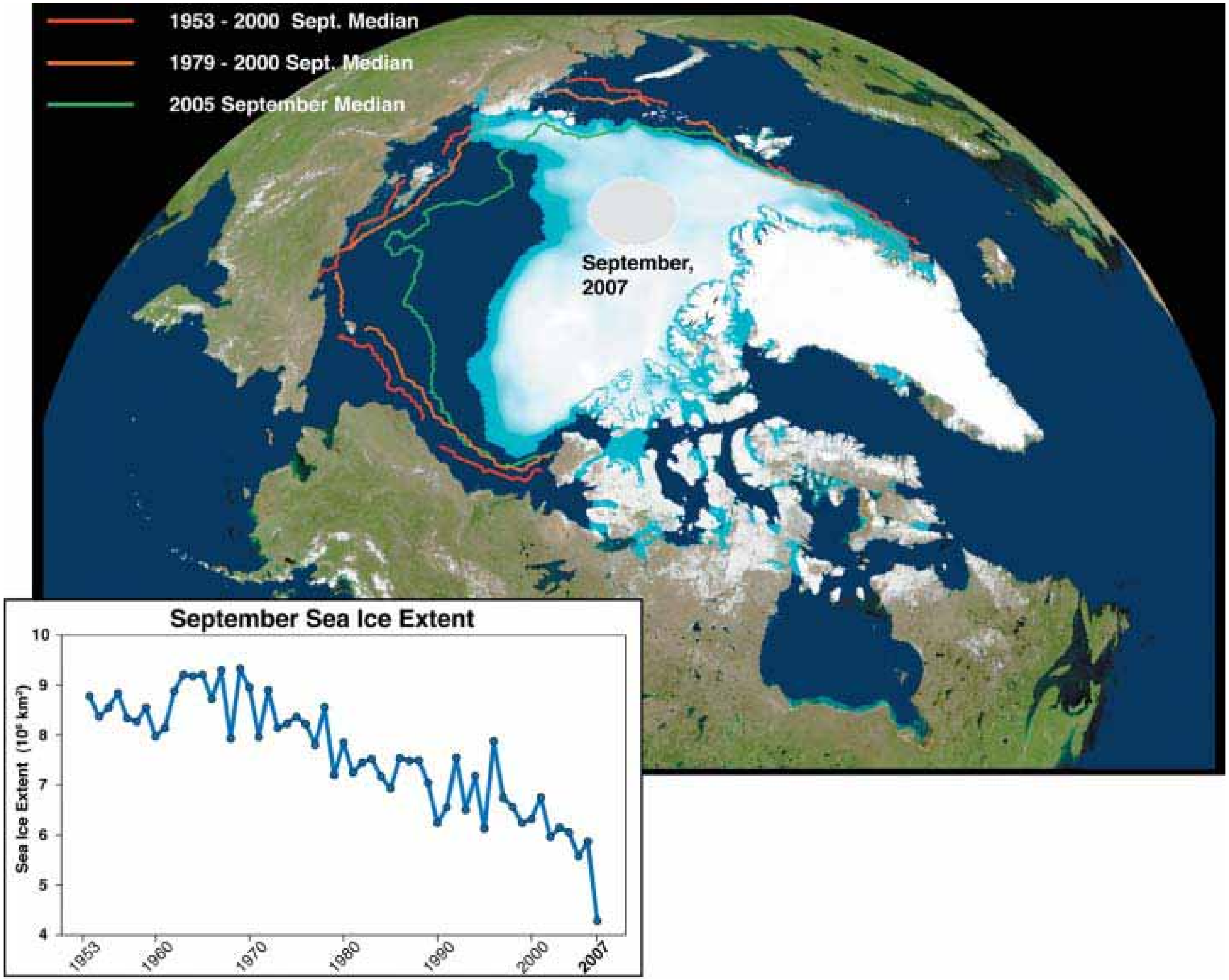
Causes of Ice Sheets Growth of Reduction

- **Warmer Ocean Temperature, T ↑:**
  Melting of bottoms of floating ice shelves and tongues of outlet glaciers → faster discharge from grounded ice → ice loss ↓
- **Warmer Air Temperature, T ↑:**
  More precipitation (snowfall) → ice growth ↑
  More melting at lower elevations → ice loss ↓

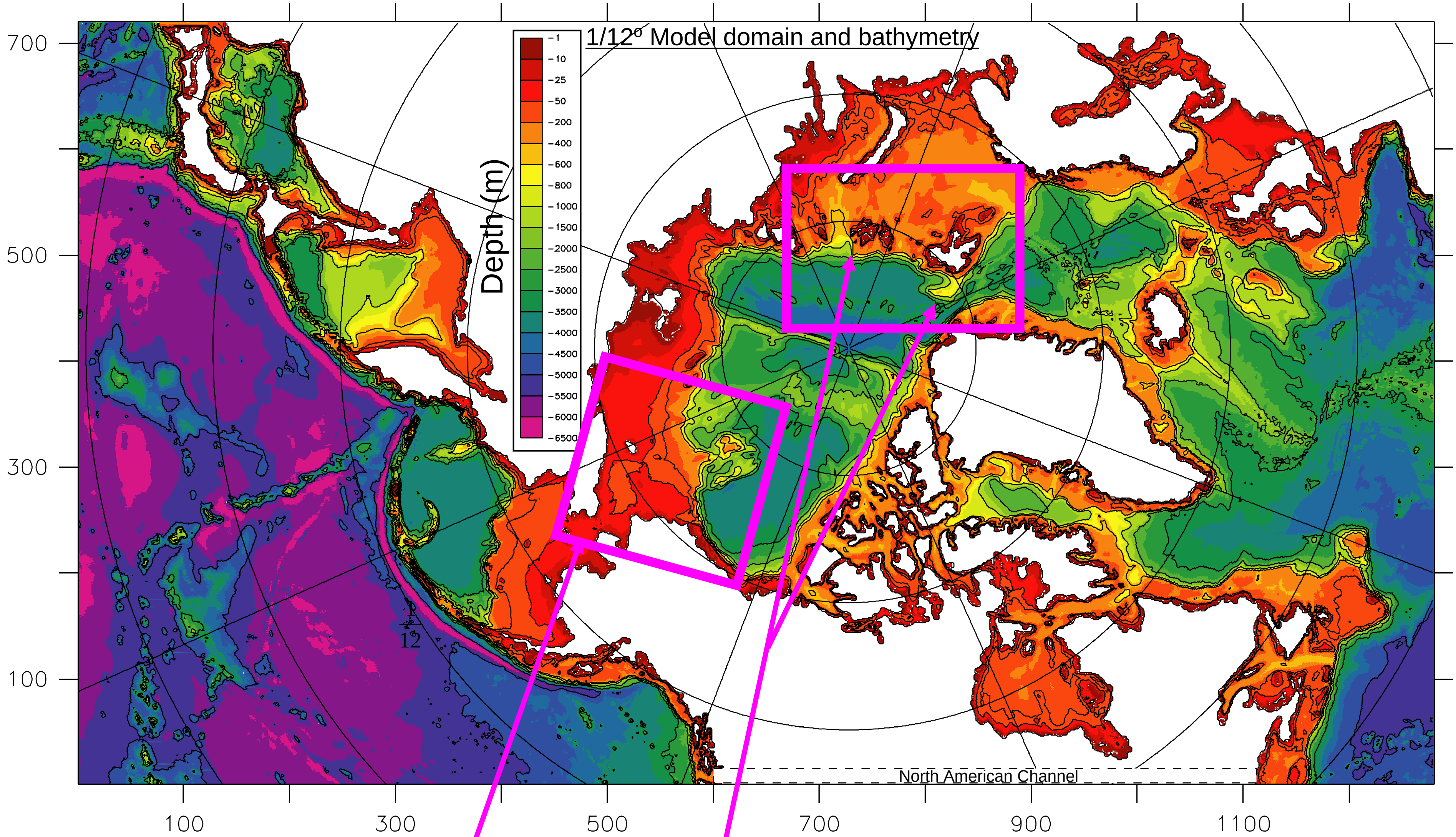
Observed rate of loss of Arctic ice extent is faster than IPCC AR4 predictions



Adapted from Stroeve et al., 2007



"Given these conservative model results, along with the remarkable events of 2007, our view is that a seasonally ice-free Arctic Ocean might be realized as early as 2030."
Stroeve et al., EOS 01/082008



Gateways/Margins of Pacific Water and Atlantic Water Inflow into the Arctic Ocean

<u>Main uncertainties of importance to global climate</u>

1. Northward heat transport from the N. Atlantic/Pacific to Arctic Ocean *
2. Arctic sea ice thickness and volume *
3. Freshwater export from the Arctic to North Atlantic

1/12° (9-km) Coupled Ice-Ocean Model

1. **Ocean Model = LANL/POP, Sea Ice Model = 'Hibler 1979'-type**
2. **New improved bathymetry**
3. **New hydrographic climatology (PHC)**
4. **Freshwater sources from runoff but no P-E fluxes**
5. **Numerical tracers for Pacific Water, Atlantic Water, and river runoff**
6. **Completed integrations:**
   - 48-year spinup with ECMWF reanalysis
   - ensemble of four 1979-2004 integrations using realistic ECMWF fields with variable surface T&S restoring (to account for P-E buoyancy flux)

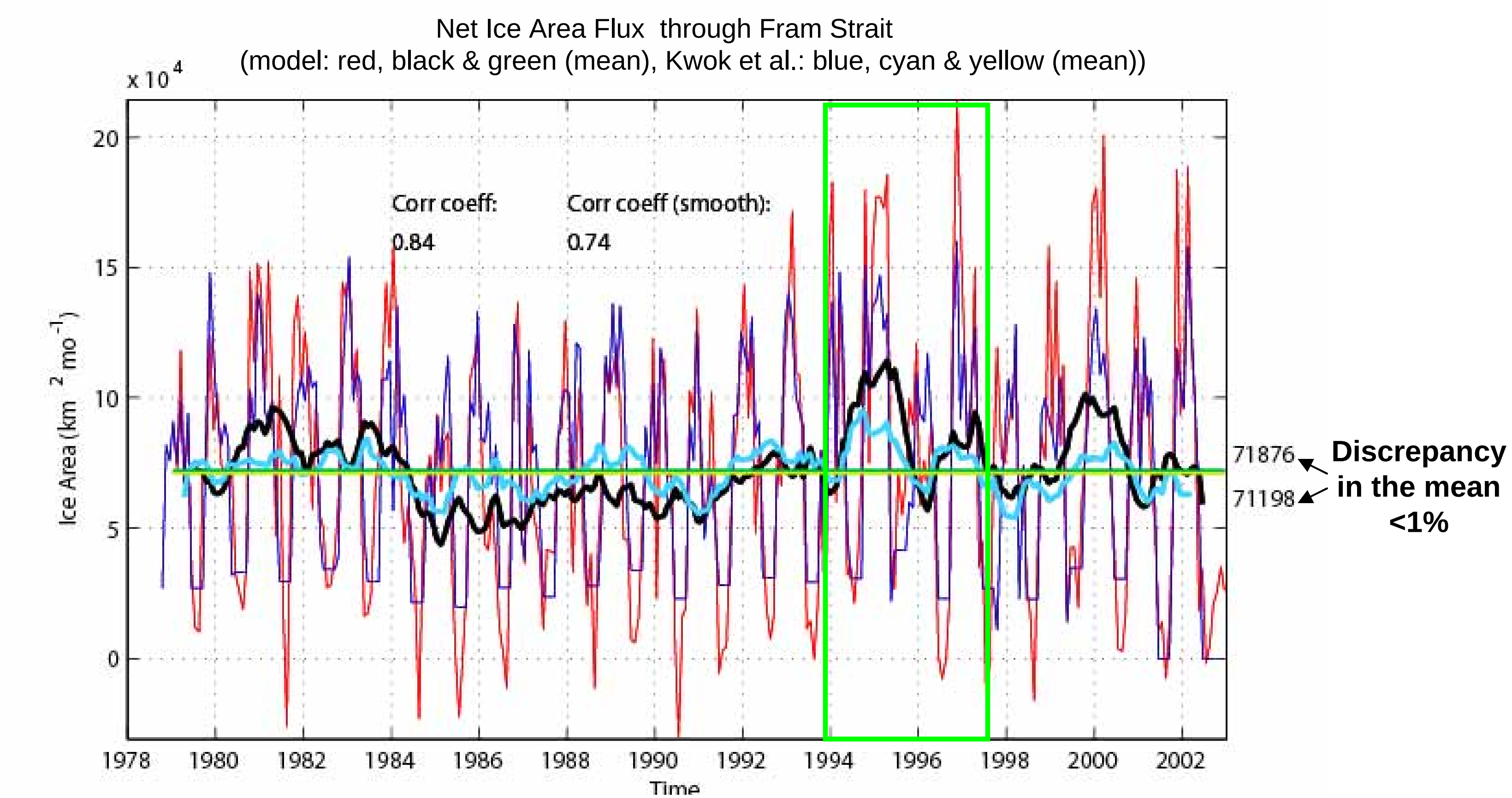
7. More information at: www.oc.nps.navy.mil/NAME/name.html

Computer resources:

Arctic Region Supercomputing Center

Comparison of area fluxes through Fram Strait (wind-driven)

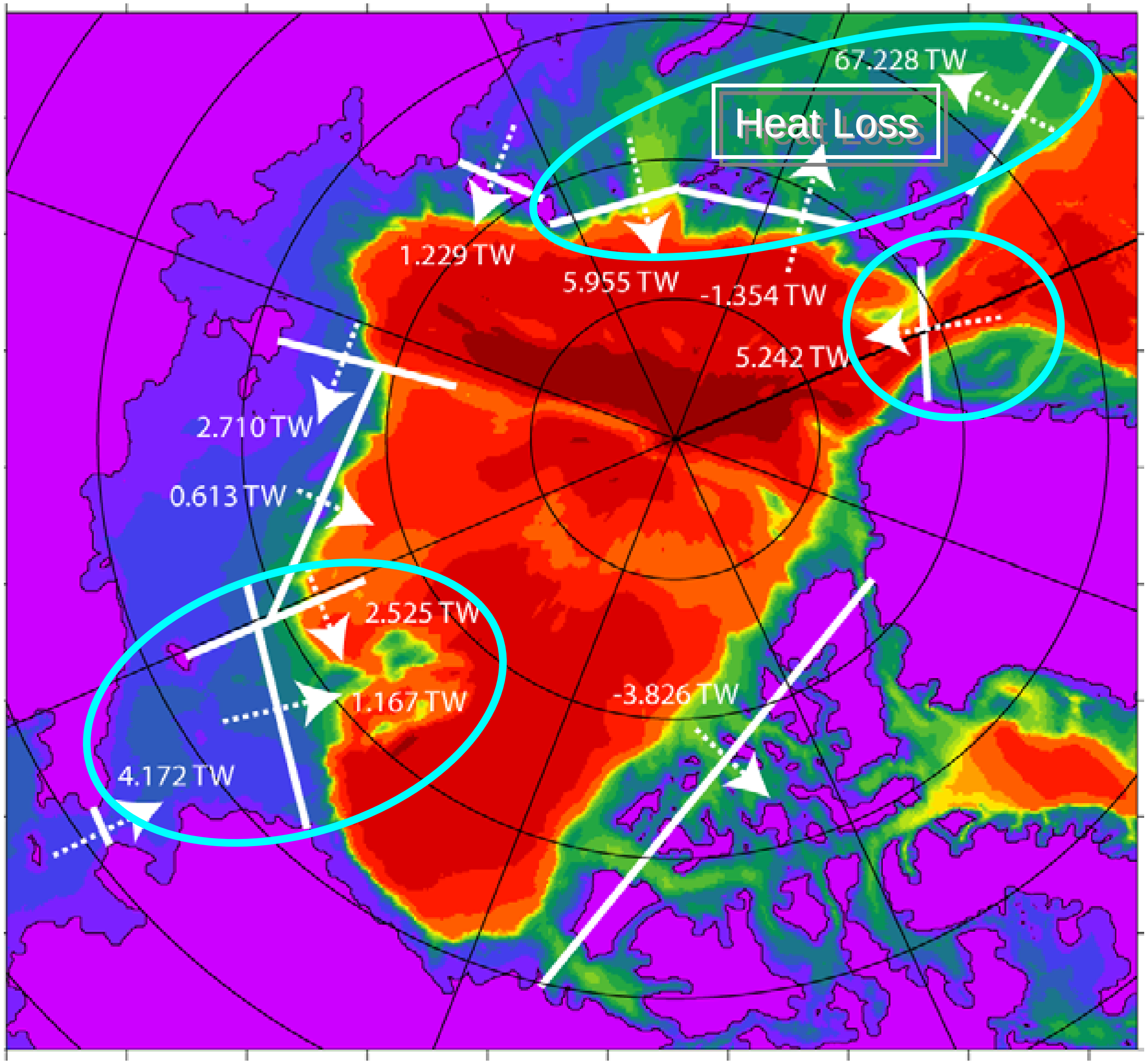
High Export in the mid 1990s!



Mean area flux [km^2/mo] estimates from satellite (Kwok et al., 2003 blue/cyan/yellow) and model (red/black/green)

- Corr. coef: 0.84 / **0.74** (but no satellite estimates May-Sep!)

1979-2004 Mean Oceanic Heat Convergence: 0-120 m; $T_{ref} = T_{freezing}$



Modeling Challenges: Inflow of Pacific / Atlantic Water into the Arctic Ocean and impacts on the sea ice

- Pacific Water entering via narrow (~60mi) Bering Strait and across Chukchi shelf

  (Clement et al., DSR II 2005)

- outflow through Fram Strait vs. Atlantic Water inflow (FSBW/BSBW)

  (Maslowski et al., JGR 2004; Stroeve and Maslowski, 2007)

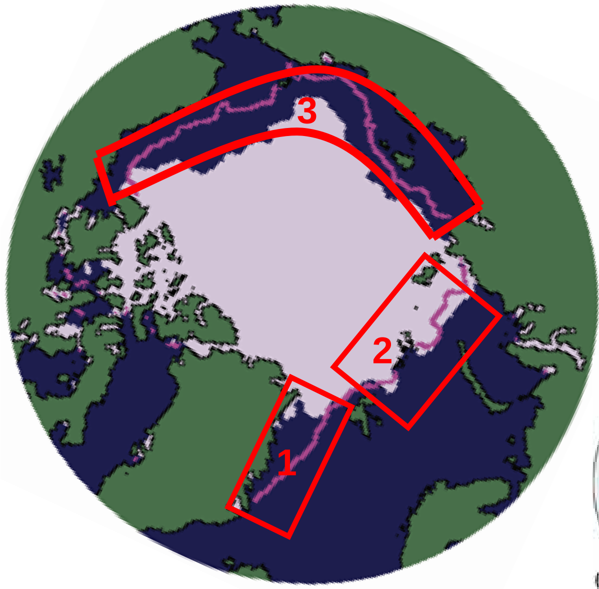
- Atlantic (BSBW) and Pacific Water each losses majority of heat to the atmosphere before entering Arctic Basin

<u>High resolution is one of the top requirements for advanced modeling of Arctic climate</u>

(Maslowski et al., 2008)

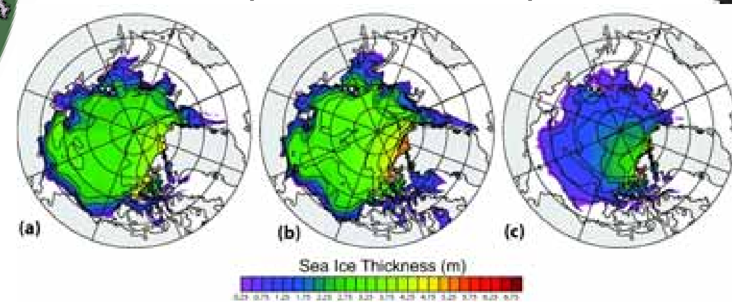
GCM Comparison: September 2002

NSIDC ice extent

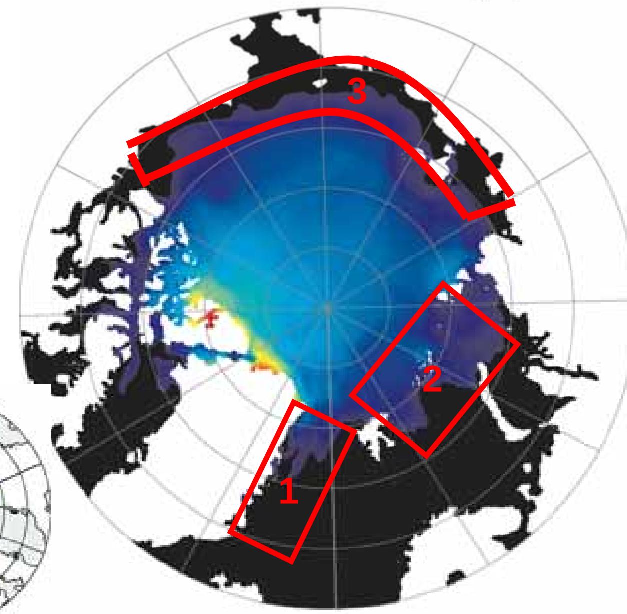


NAME sea ice thickness (m) in (a) 1982, (b) 1992, (c) 2002

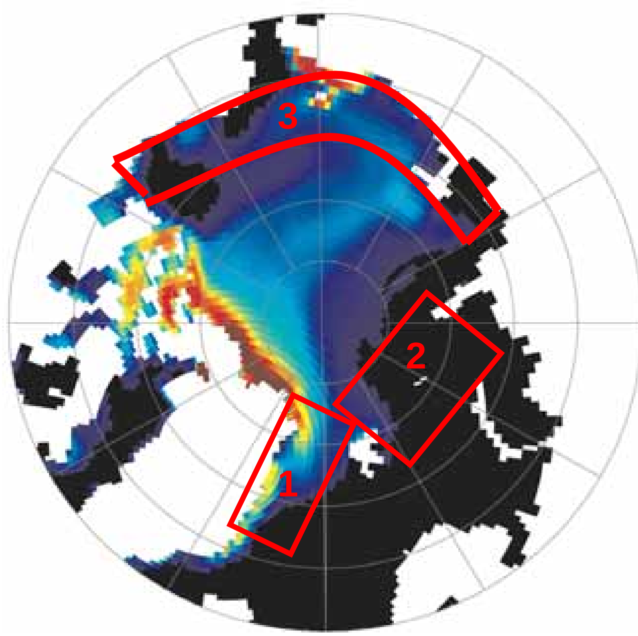
(Maslowski et al., 2007)

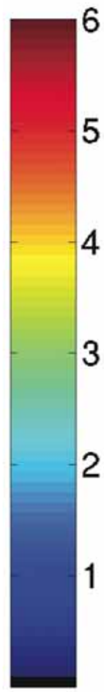


NAME Ice Thickness (m)

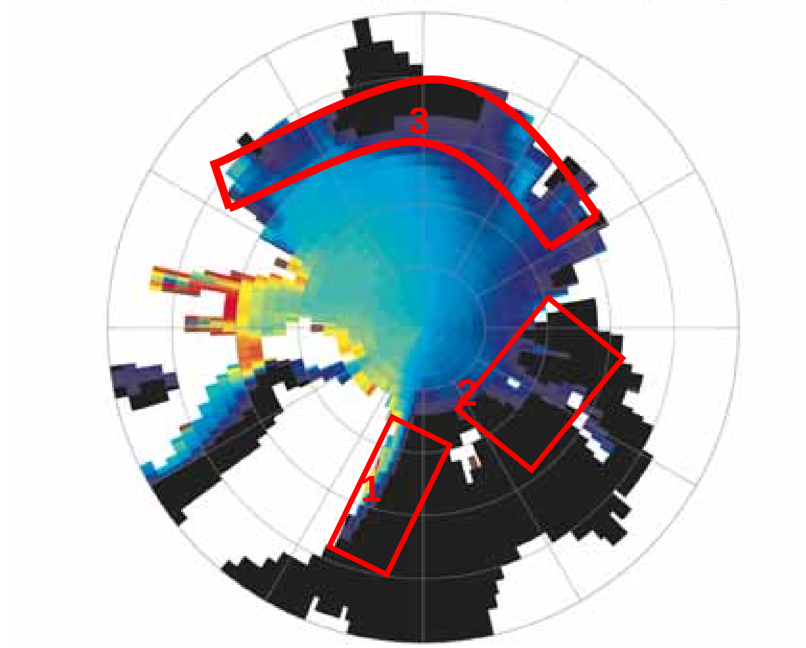


CCSM3 Ice Thickness (m) - ES01(b)

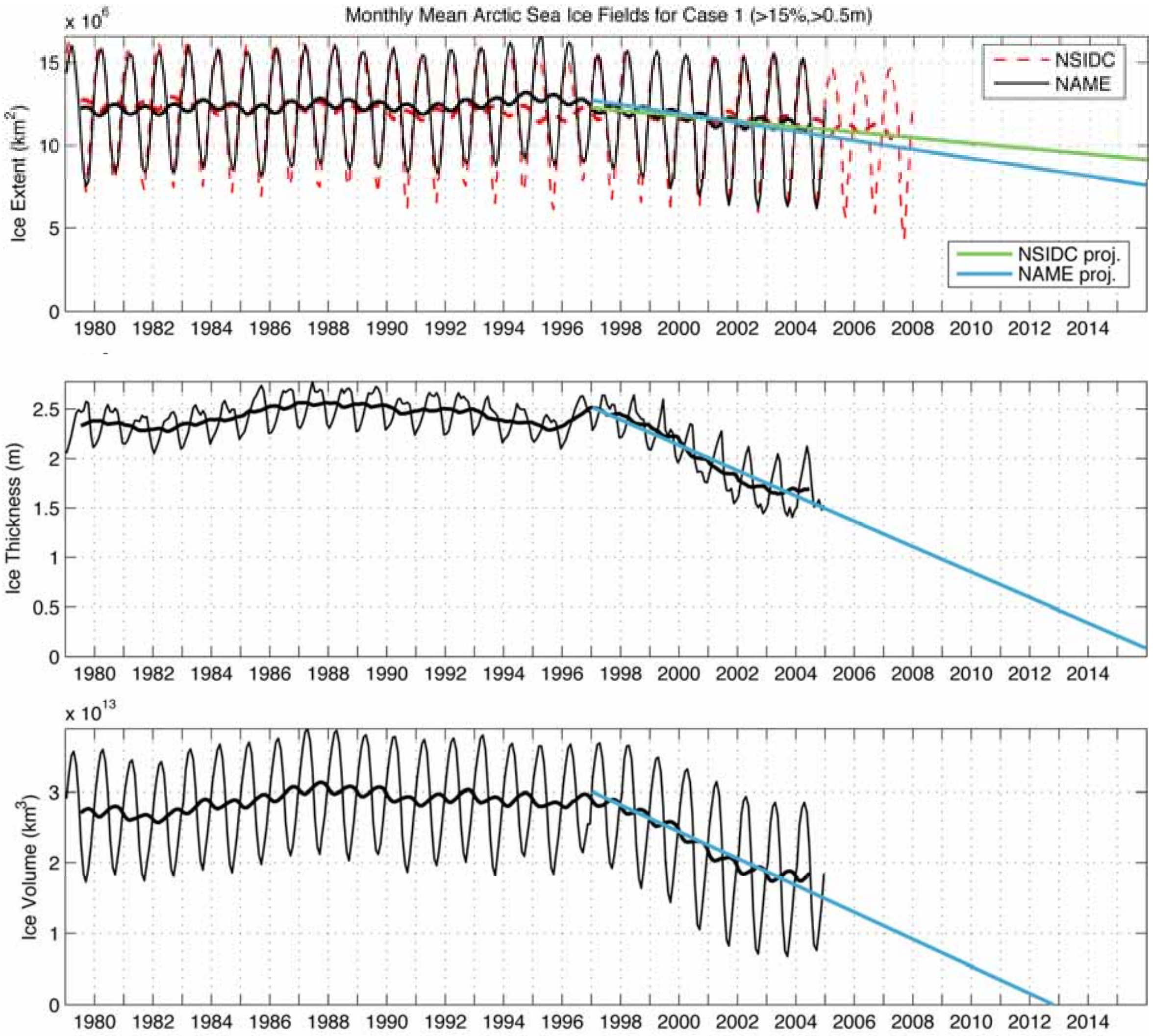




HadGEM1 Ice Thickness (m) - sresa1b(run1) - Sep 2002



79-04 time series of Ice Extent, Thickness, and Volume



Between 1997-2004:

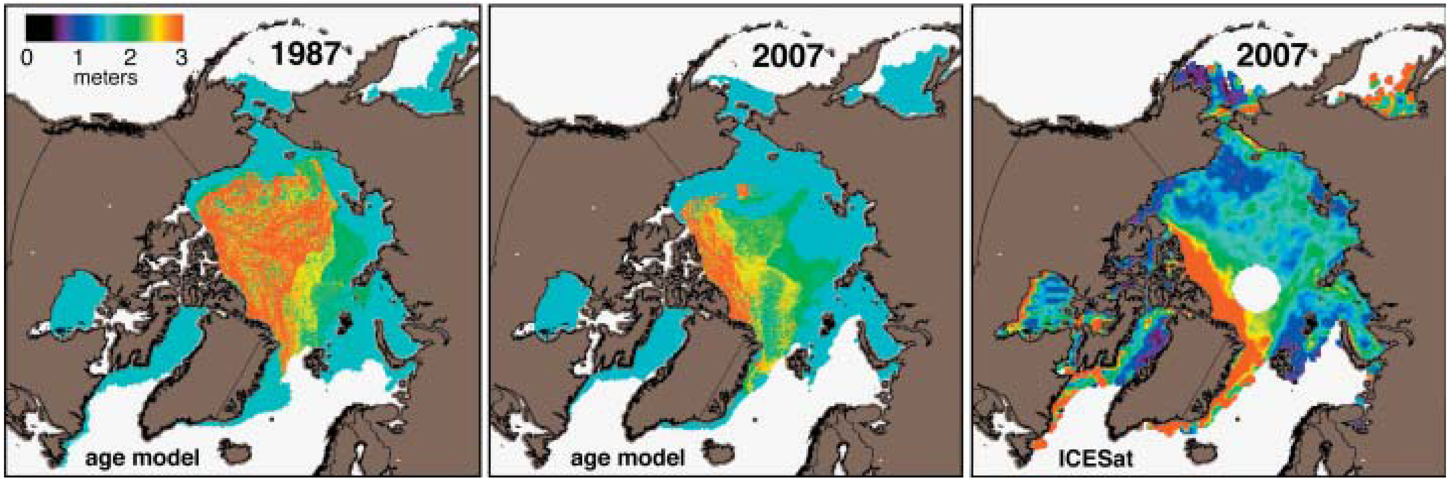
- annual mean sea ice concentration has decreased by ~17%
- mean ice thickness has decreased by ~0.9 m or ~36%
- ice volume decreased by 40%, which is >2x the rate of ice area decrease

If this trend persists the Arctic Ocean will become ice-free by ~2013!

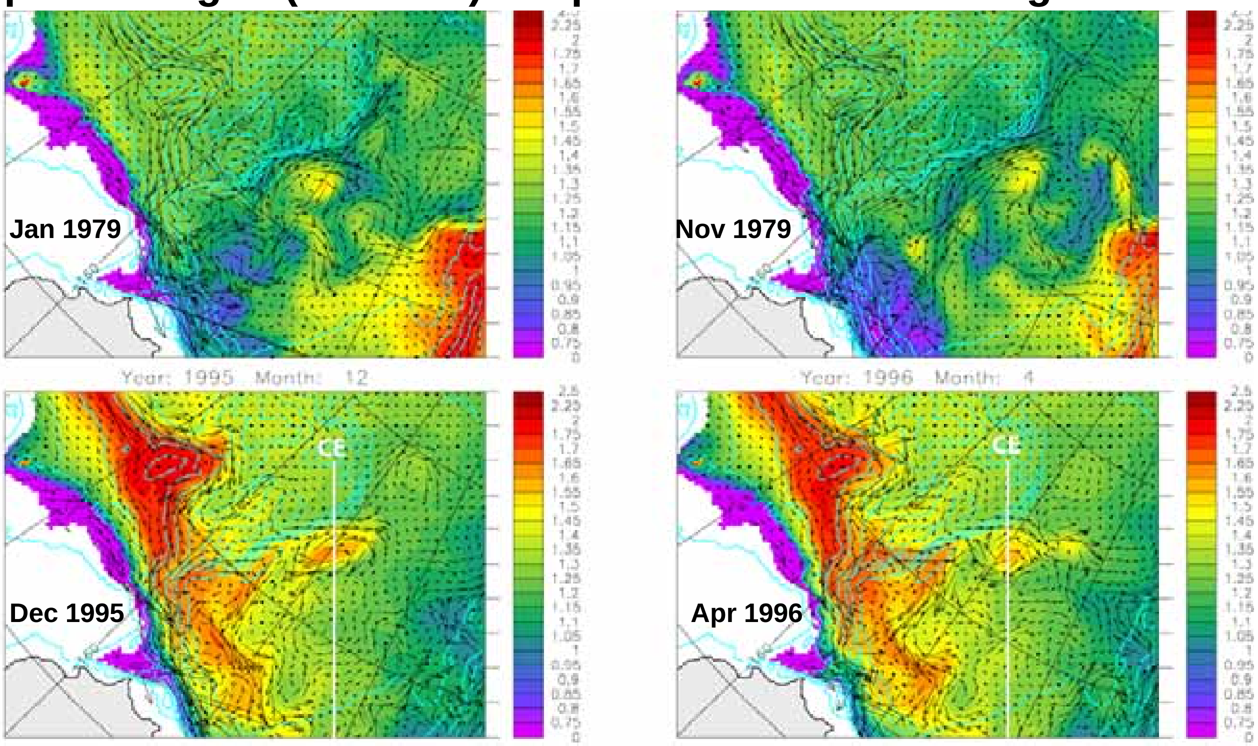
Conclusions #1

1. The rate of decrease of sea ice thickness and volume possibly about 2x greater than that of sea ice extent
2. Anomalous export of sea ice through Fram Strait during the mid-1990s a precursor of sea ice decline
3. Oceanic heat advection has contributed significant forcing (>60%) to sea ice melt during the last decade
4. CCSM3/HadGEM1 (and potentially many other GCMs) simulations need an improved representation of the Arctic Ocean
5. Dedicated computer resources needed to advance Arctic and global climate modeling and prediction

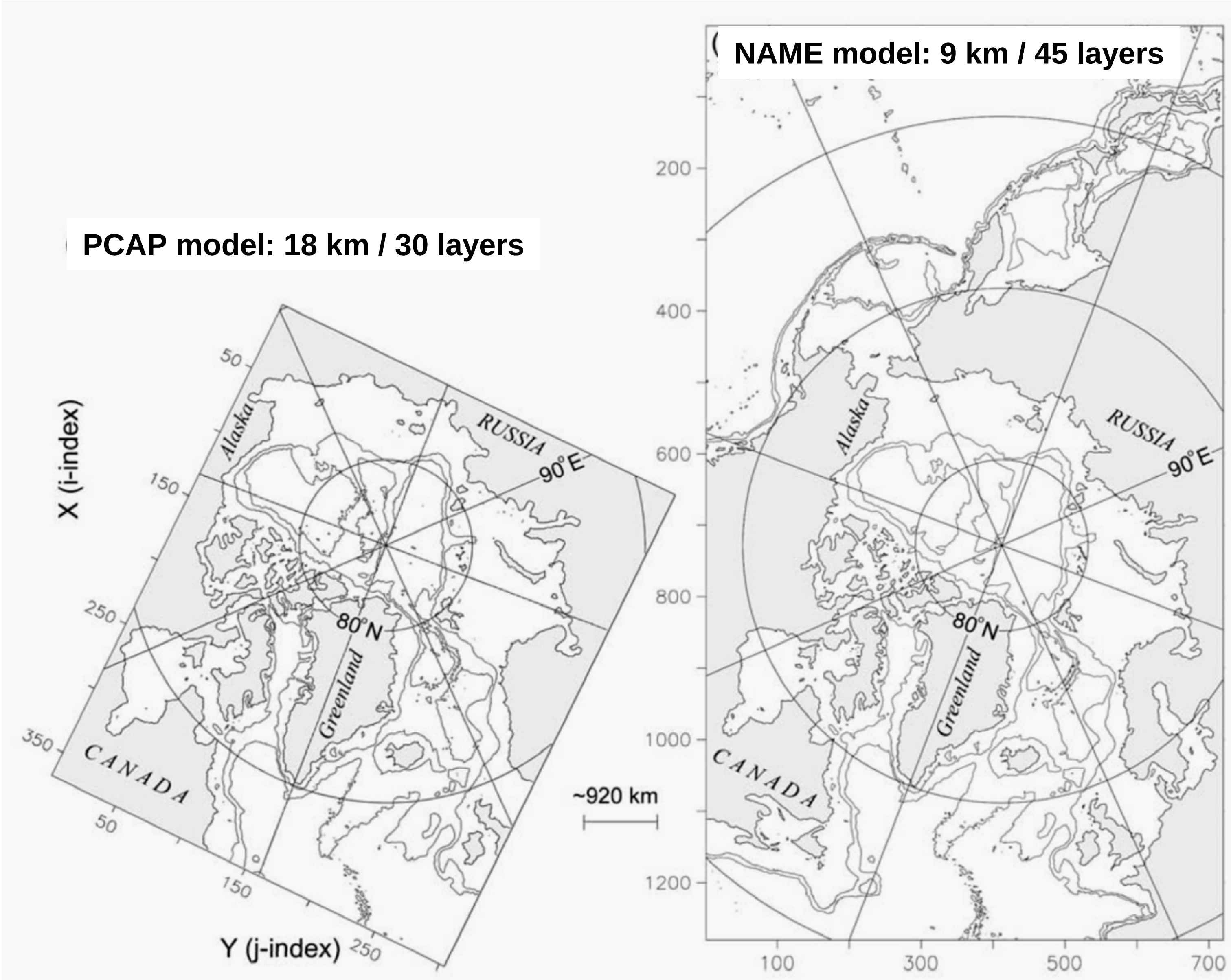
Ice Thickness estimates based on age (a) 1987, (b) 2007, and ICESat freeboard (c) 2007



Depth-averaged (65-120m) temperature above freezing and velocity

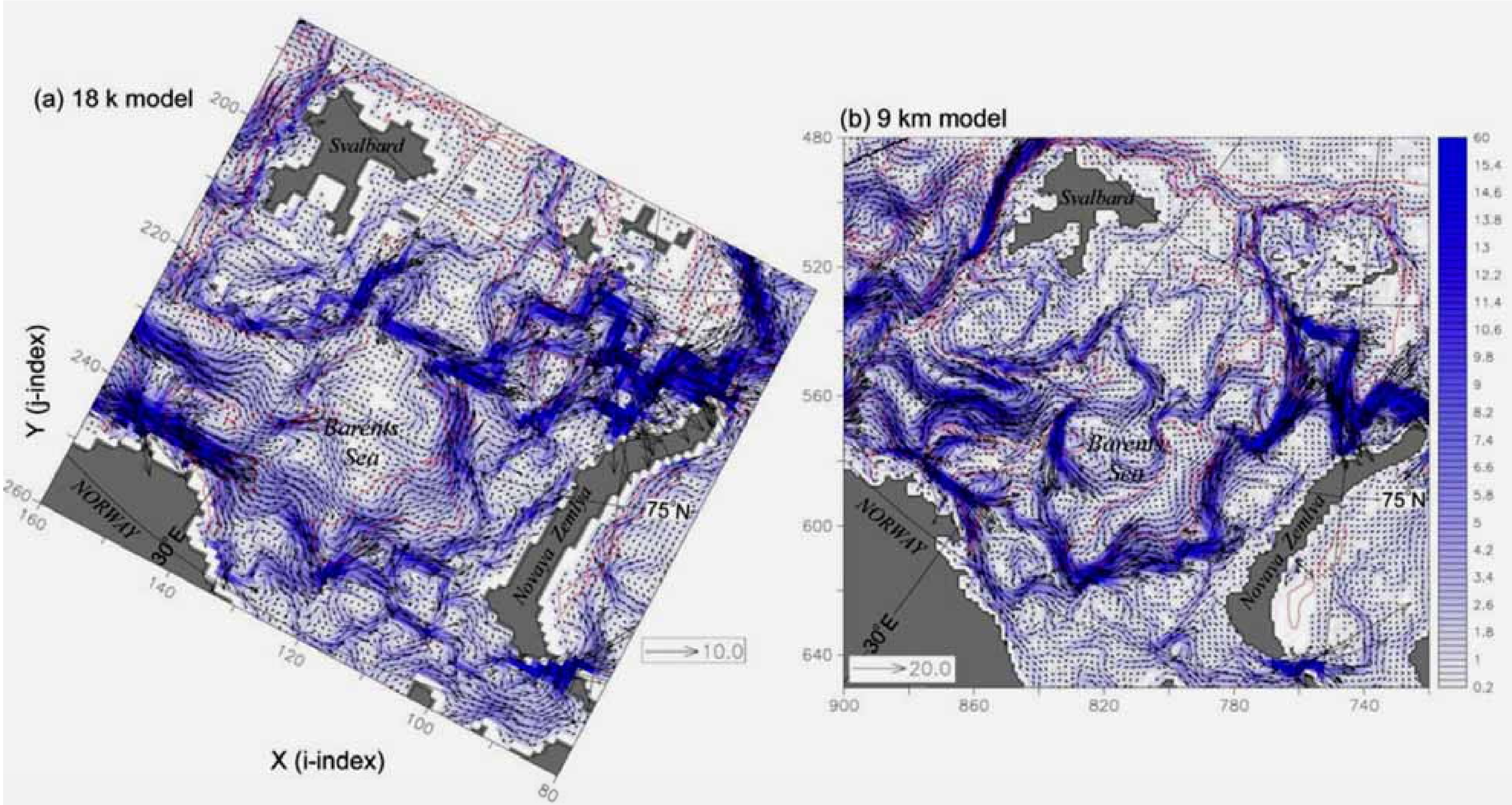


Increasing impact of eddy-driven oceanic heat advection in the western Arctic

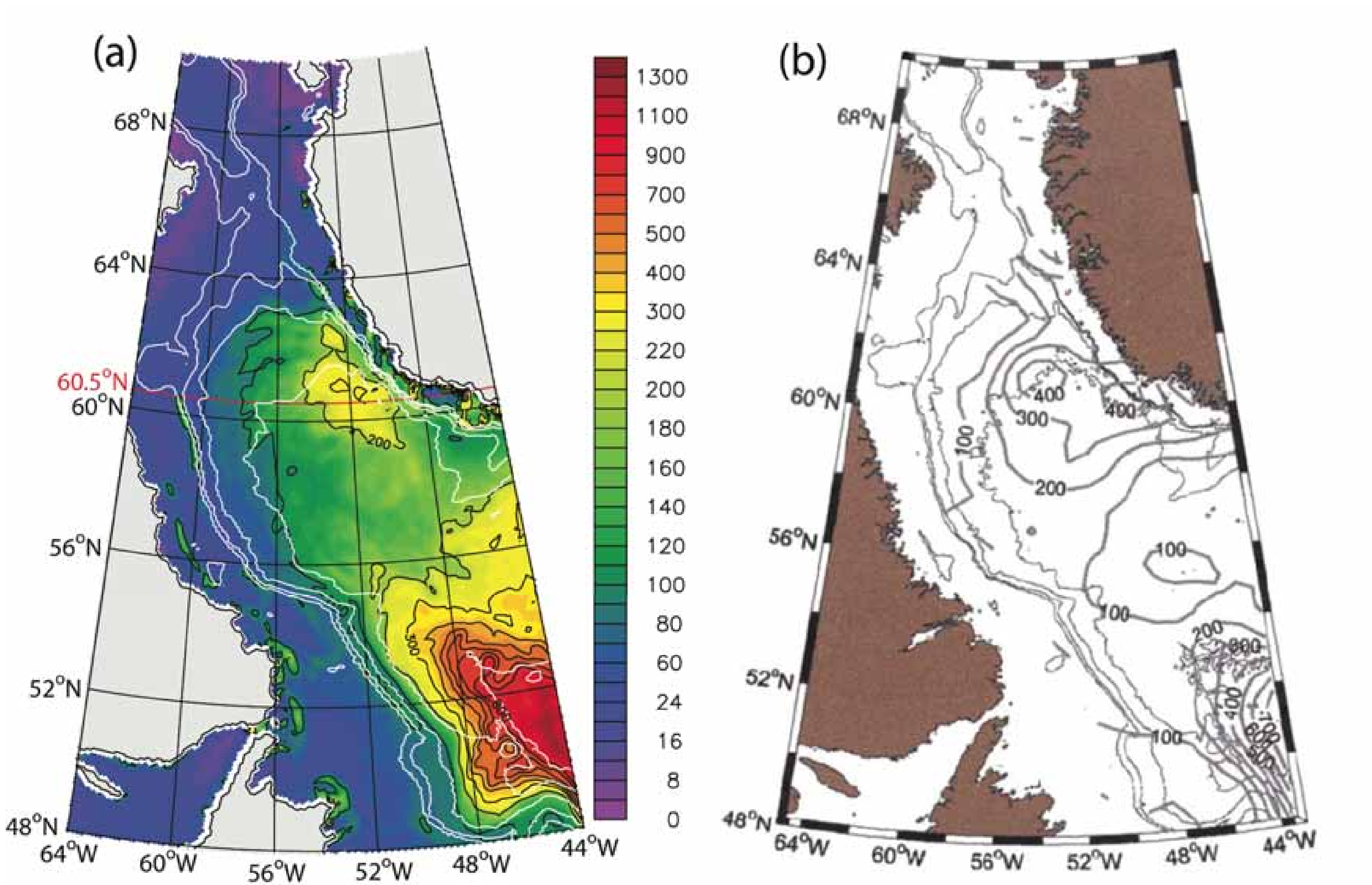


18-km PCAP model domain (a) and 9-km NAME model domain (b). 18-km model image has been rotated 26°.

Impacts of spatial resolution and bathymetry

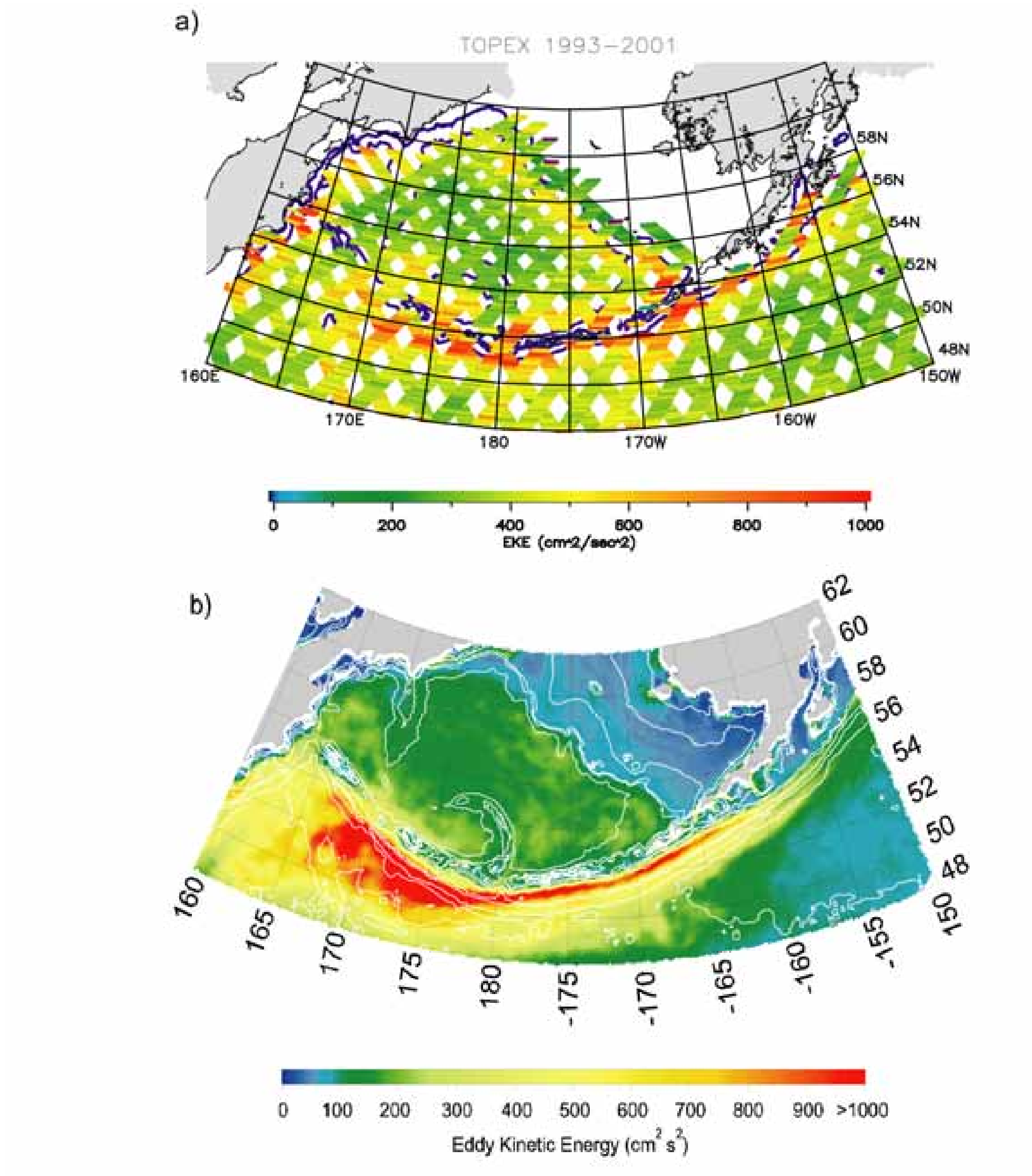


1980 annual mean velocity (cm/s) in the Barents Sea. (a) PCAP, 0-225 m (model levels 1-7), every vector is plotted; (b) NAME, 0-223 m (model levels 1-15), every other vector is plotted. Background shading is current speed (cm/s) and is the same for both model images. Note the differing vector scales.

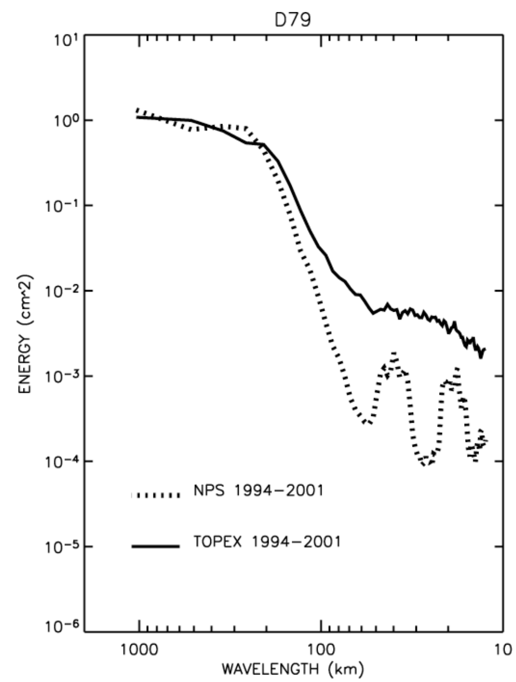


Horizontal distribution of eddy kinetic energy ($cm^2 s^{-2}$) in the Labrador Sea. (a) 1993-1997 annual mean, 0-5 m (model level 1) calculated from daily model output. EKE contours 100, 200, 300, 400, 500, 600, 700 and 800 $cm^2 s^{-2}$ in black; (b) Eddy kinetic energy deduced from surface drifter data released in North Atlantic Ocean and Labrador Sea in during 1993-1997. [After *Cuny et al., 2002*].

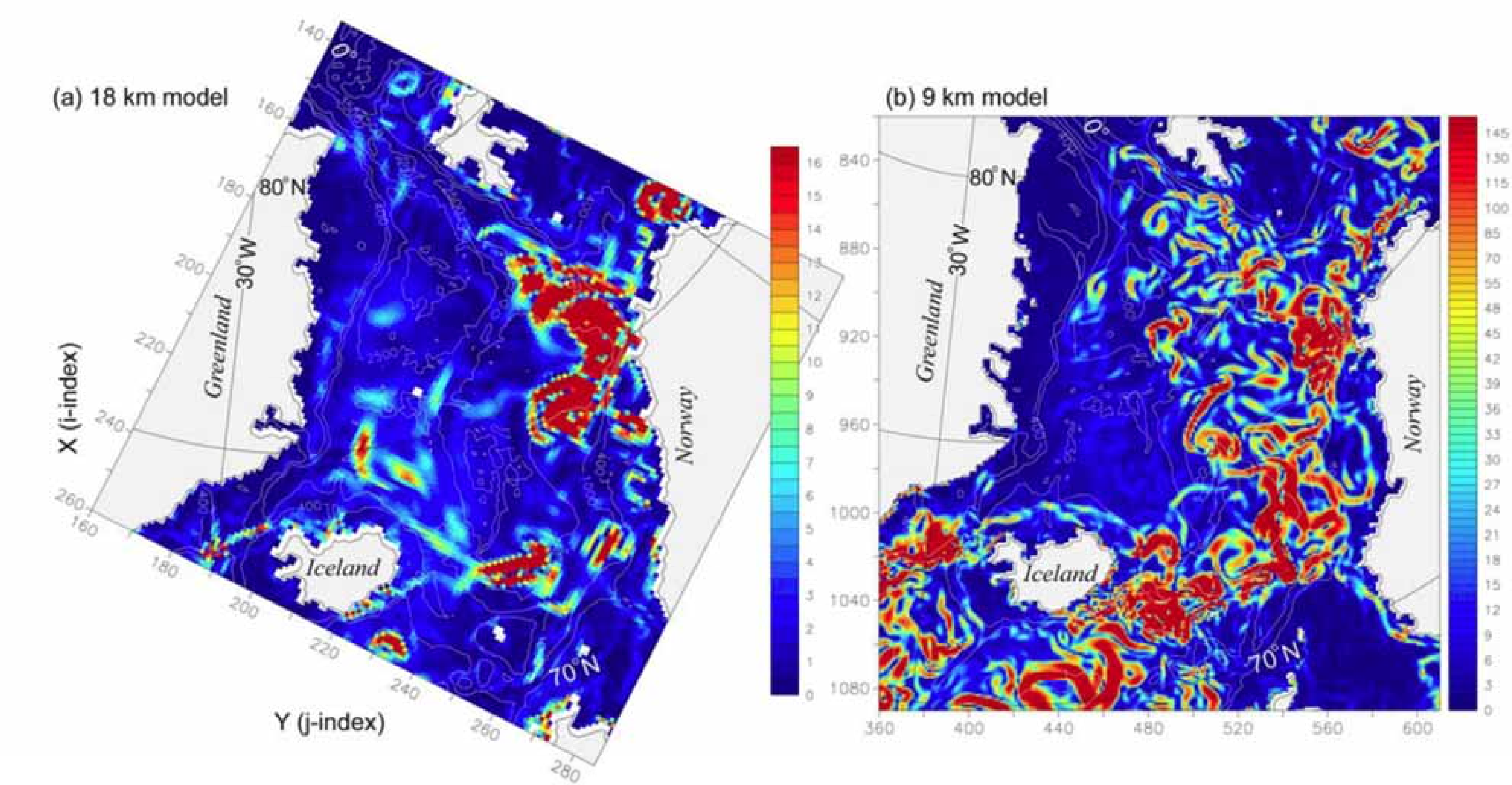
1993-2001 EKE as computed from (a) TOPEX and (b) model surface velocities



Spectra of energy as a function of wavelength



- **Model shows realistic distribution**
- **Energy at wavelengths <100 km are somewhat underestimated**
- **Smaller eddies not represented**



August 1980 snapshot of surface layer eddy kinetic energy (cm^2/s^2) in the Nordic Seas: (a) PCAP, 0-45 m (model levels 1-2); (b) NAME, 0-43 m (model levels 1-7). Note the different shading scales.

Model	Labrador Sea EKE			Nordic Seas EKE		
	Maximum	Mean	Std Dev	Maximum	Mean	Std Dev
PCAP58	132.50	4.90	9.20	269.40	4.70	13.30
PIPS	3998.00	70.40	203.70	4959.00	43.50	142.70

Conclusions #2

- **order of magnitude increase in EKE between 18 km and 9 km model configurations**

- **at 9 km realistic representation of EKE distribution in the Labrador Sea, Gulf of Alaska and Bering Sea**

• **observational estimates of EKE needed for the Arctic Ocean and other sub-Arctic regions**

• **0(1km) spatial resolution required for eddy-resolving models of the Arctic Ocean**

RAMC – DOE Funded Project Overview

Towards Advanced Understanding and Predictive Capability of Climate Change in the Arctic using a High-Resolution Regional Arctic Climate System Model

Participants:

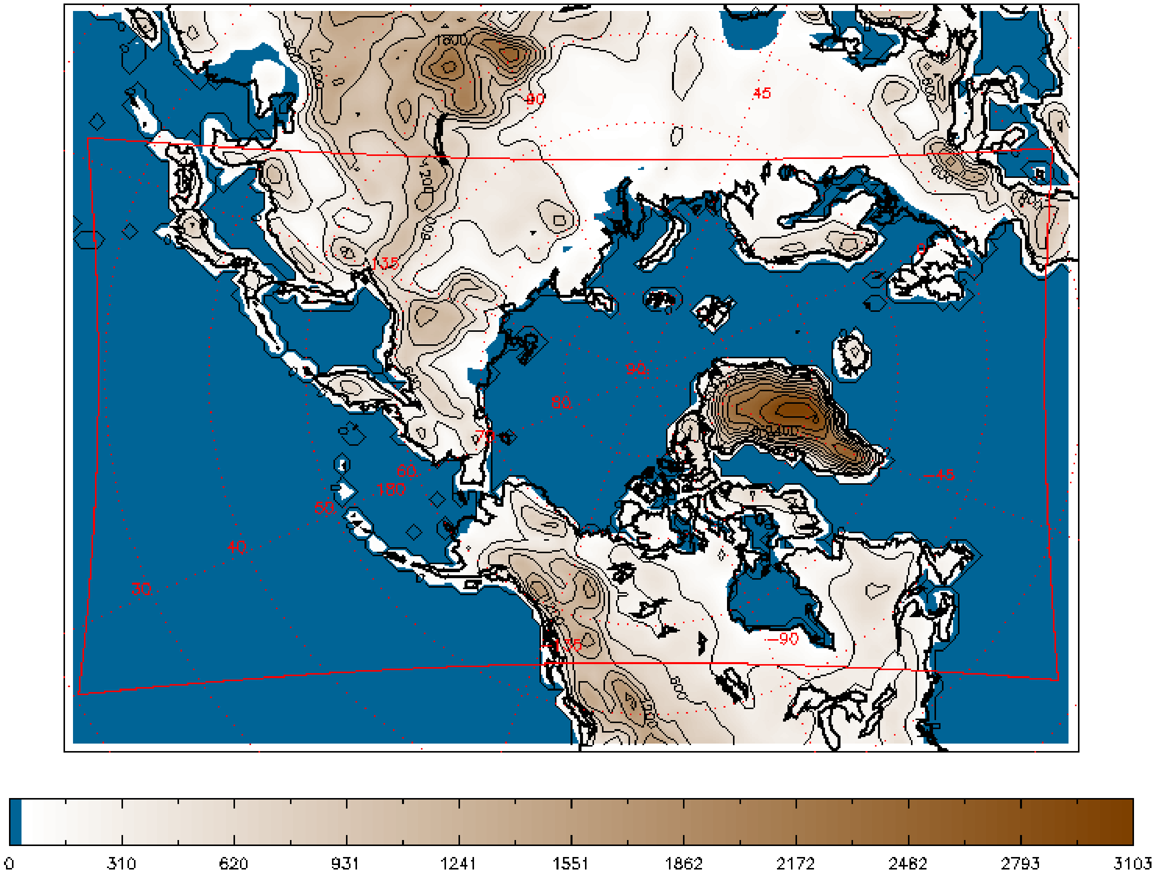
Wieslaw Maslowski	- Naval Postgraduate School
John Cassano	- University of Colorado
William Gutowski	- Iowa State University
Dennis Lettenmeier	- University of Washington

Primary science objective: to synthesize understanding of past and present states and thus improve decadal to centennial prediction of future Arctic climate and its influence on global climate.

Proposed Arctic climate system model domain and elevations

(red box represents the domain of ocean and sea ice models)

Panarctic Domain Elevation



Pan-Arctic region to include:

- all sea ice covered ocean in the northern hemisphere
- Arctic river drainage
- critical inter-ocean exchange and transport
- large-scale atmospheric weather patterns (AO, NAO, PDO)

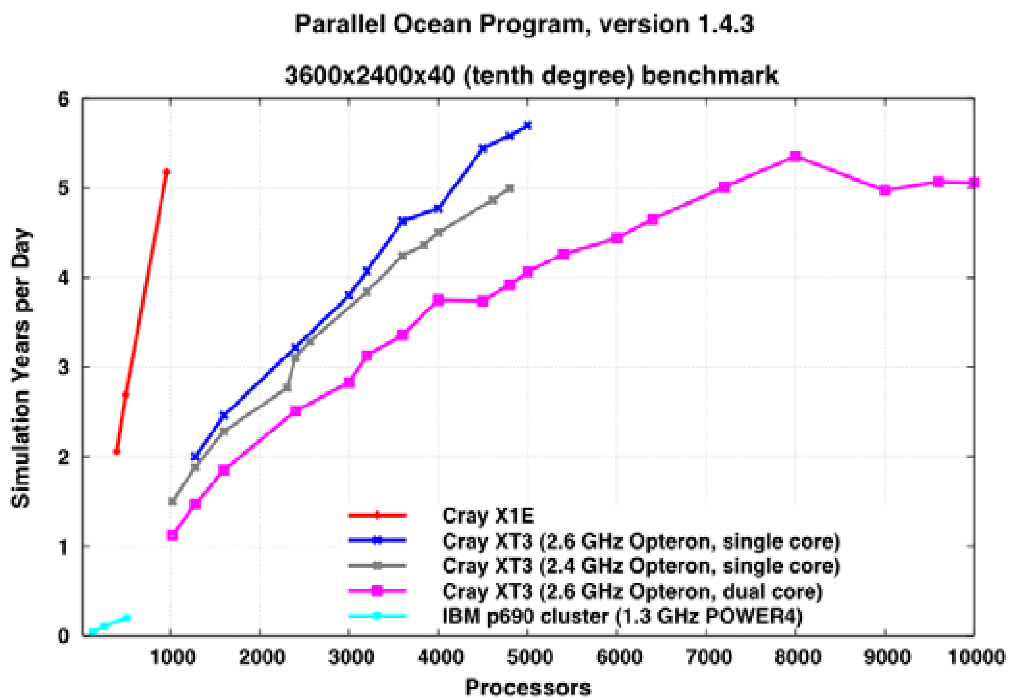
RACM
Model components and resolution

- **Atmosphere - Polar WRF** (gridcell ≤50km)
- **Land Hydrology - VIC / CLM / Noah** (gridcell ≤50km)
- **Sea Ice - LANL/CICE** (gridcell ≤10km)
- **Ocean - LANL/POP(HYPOP)** (gridcell ≤10km)
- **Flux Coupler** (based on NCAR/CCSM global model coupler)

POP

- Current release
  - 2.0.1
  - Partial bottom cells
  - Tripole grid support
  - Flexible decomposition for tuning performance
- New release (coming soon)
  - New load balancing distribution (J. Dennis)
  - Improved barotropic solver performance
  - New parameterizations, diagnostics (floats)
  - Tracer infrastructure for biogeochemistry

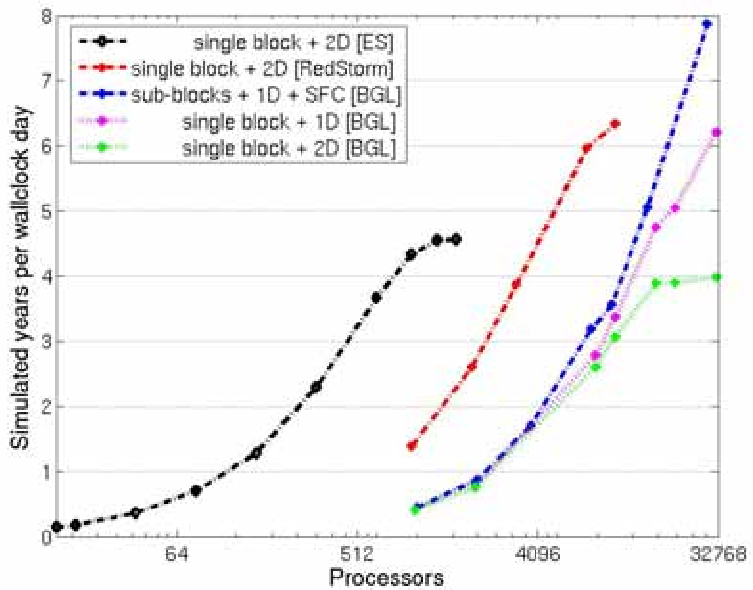
POP Performance



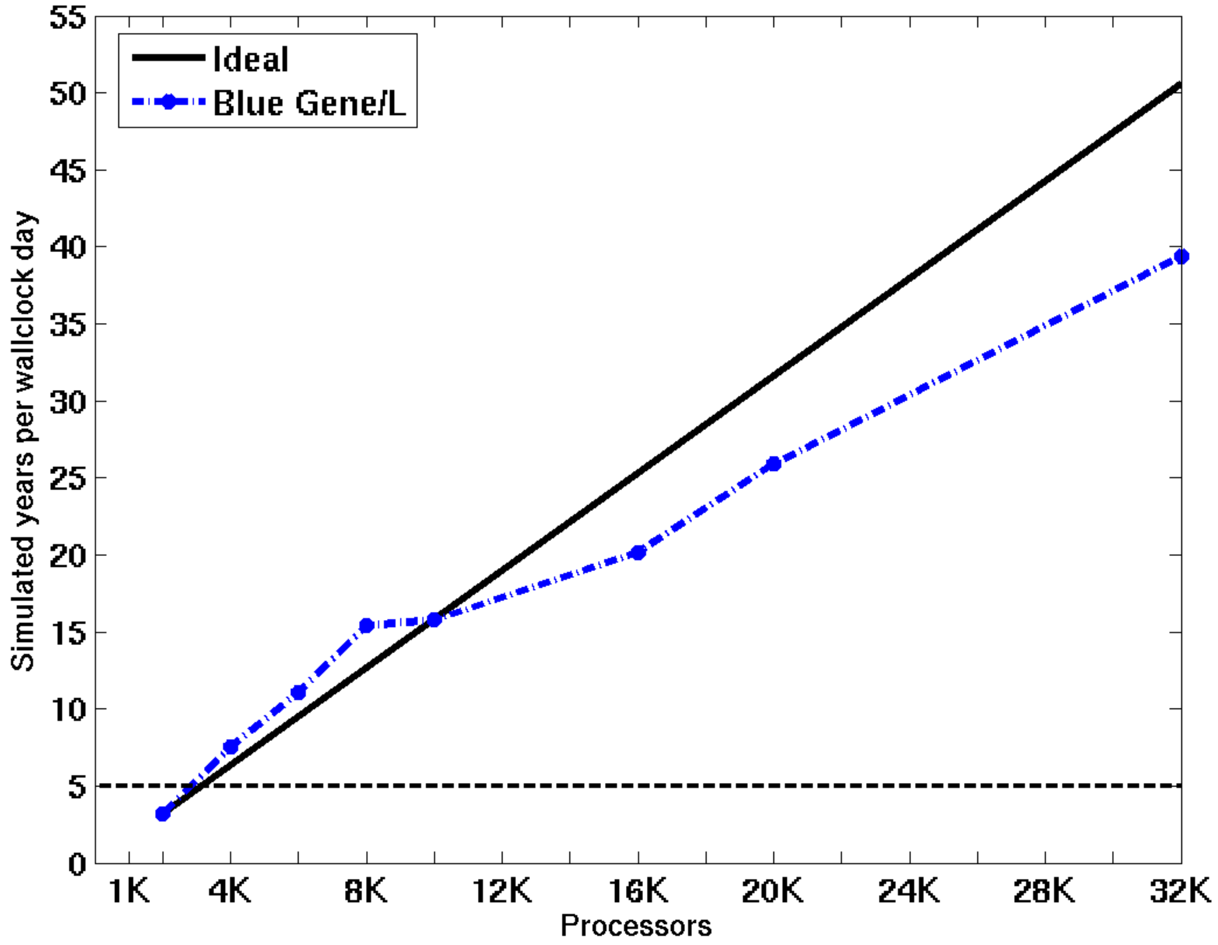
Cray performance – these numbers have recently been substantially improved (Courtesy P. Worley, J. Levesque)

Scales to large processor counts
(1/10 degree benchmark)

POP 2.0 Results on Earth Simulator, Red Storm and Blue Gene (courtesy Y. Yoshida, M. Taylor, J. Dennis)



CICE performance on IBM BG/L.



Courtesy of P. Lipscomb and E. Hunke of LANL

Computational Requirements Estimates

- RACM – equivalent of 10 Mln proc-hrs of Cray XT4 plus 50TB of storage

- 1/48º (2.3-km) Pan-Arctic POP-CICE
  - equivalent of 2-3 Mln proc-hrs per decade
  - ERA40 reanalysis integration since the late 1950s
  - around 300 TB of storage
  - 2.5 Mln proc-hrs allocated through HPCMP Capacity Application Project on the Cray XT5 at ARSC
  - Dedicated resources needed for future integrations