Arctic Ocean Model Intercomparison Project (AOMIP)

Andrey Proshutinsky, *Woods Hole Oceanographic Institution*

and

AOMIP team

Evaluation of the Use of Hindcast Model Data for OSRA in a Period of Rapidly Changing Conditions

March 30, 2011 , SAIC, McLean, Virginia

AOMIP is supported by the Office of Polar Programs of the National Science Foundation

Bergen: 14-16 June 1999

Modelling and sources: A Workshop on Techniques and Associated Uncertainties in Quantifying the Origin and Long-Range Transport of Contaminants to the Arctic

"all models are wrong … some are useful"

AMAP

Arctic monitoring and Assessment Programme

Outline:

- ***Introduction (motivation and history)***
- ***AOMIP goals and objectives***
- ***Major results***
- ***AOMIP studies in the Chukchi and Beaufort Seas***
- ***Concluding remarks***

AOMIP is supported by the Office of Polar Programs of the National Science Foundation

In addition, I will pay some more attention:
(due to cancellation of talk "Cross Section of Models - Strengths and Weaknesses" by Dr. Enrique Curchitser, Rutgers University)

- **Vertical and horizontal model discretization (z- versus sigma- versus isopycnal and terrain-following models; structured and unstructured grid models)**

- **Ice model characteristics and sea ice dynamics reology**

- **Data assimilation needs**

- **Regional models versus global and downscaling problems**

- **Reproduction and/or parameterization of vertical and horizontal mixing, tides, atmospheric loading, river runoff**

The AOMIP is an international effort to identify systematic errors in Arctic Ocean models and to reduce uncertainties in model results and climate predictions.

AOMIP was initiated in September 2000 and was supported:

- in 2001-2002 by NOAA via the University of Alaska Cooperative Institute for Arctic Research,

- in 2003-2006 by OPP NSF via IARC,

- and since 2007 by a direct grant from OPP NSF. This project has created a broad-based international community of Arctic marine modelers and some observationalists.

AOMIP initiation and expectations

AOMIP initial goal was to provide:

1. Recommendations for improving existing regional and global coupled ice-ocean models;

2. Assessments of the degree of uncertainty in the results and conclusions made by different modelers, scientific groups and institutions.

3. Identification of model errors and causes of these errors and model discrepancies.

At present, the AOMIP group consists of a core of seven principal investigators, and a large number of co-investigators from different countries. A new web site for the AOMIP project is located at http://www.whoi.edu/projects/AOMIP

Project Principal Investigator: A. Proshutinsky, WHOI, USA

Co-Principal Investigators

Eric CHASSIGNET, FSU, USA
Changsheng CHEN, UMASSD, USA
Chris HILL, MIT, USA
David HOLLAND, NYU, USA
Mark JOHNSON, UAF, USA
Wieslaw MASLOWSKI, NPS, USA
Michael STEELE, PSC/UW, USA

Co-Investigators:

There are approximately 22 active co-Investigators from USA, Canada, Russia, United Kingdom, France, Sweden, Norway, Denmark, and Germany. In addition there are approximately 60 active recipients of AOMIP information who participate in AOMIP activities from time to time or use AOMIP results and recommendations

Note that 5 speakers at this meeting are active AOMIPers:

1. Greg Holloway
2. Mike Steele
3. Wieslaw Maslowski
4. Andrey Proshutinsky
5. Xiangdong Zhang

Institute, PI(s)	Country	Abbreviation
Arctic and Antarctic Research Institute, A. Makshtas	Russia	AARI
Alfred Wegener Institute, R. Gerdes and C. Koeberle	Germany	AWI
Dalhousie University, F. Dupont	Canada	DAL
Florida State University, E. Chassignet and D. Dukhovskoy	USA	FSU
Geophysical Fluid Dynamics Laboratory, S. Griffies, M. Winton	USA	GFDL
Goddard Space Flight Center, S. Hakkinen	USA	GSFC
International Arctic Research Center, B. Hibler, G. Panteleev	USA	IARC
Institute of Marine Sciences, UAF, M. Johnson	USA	IMS
Institute of Ocean Sciences, G. Holloway	Canada	IOS
Jet Propulsion Laboratory, R. Kwok, A. Nguyen	USA	JPL
Los Alamos National Laboratory, E. Hunke	USA	LANL
Massachusetts Institute of Technology, C. Hill	USA	MIT
Naval Postgraduate School, W. Maslowski	USA	NPS
National Center for Atmospheric Research, M. Holland	USA	NCAR
New York University, D. Holland	USA	NYU
Norwegian Polar Institute, Ole Anders Nøst	Norway	NPI
Ocean and Atmosphere Systems, M. Karcher and F. Kauker	Germany	OASYS
Proudman Oceanographic Laboratory, M. Maqueda	UK	POL
Russian Academy of Science, Moscow, N. Yakovlev	Russia	RASM
Russian Academy of Science, Novosibirsk, E. Golubeva	Russia	RASN
Swedish Meteorological and Hydrological Institute, M. Meir	Sweden	SMHI
University College London, S. Laxon	UK	UCL
University of Massachusetts, Dartmouth, C. Chen	USA	UMAS
University of Washington, M. Steele, J. Zhang	USA	UW
Woods Hole Oceanogr. Ins, A. Proshutinsky, P. Winsor, A.	USA	WHOI

AOMIP 2008-2011: Participants

- 25 institutions are involved in AOMIP studies in the current research cycle.

Regional AOMIP Models

AOMIP Model ID	AWI	GSFC	IARC	ICMMG	IOS	LLN
Home Institute	Alfred Wegener Institute	Goddard Space Flight Center	International Arctic Research Center	Institute of Computational Mathemetics and Mathematical Geophysics	Institute of Ocean Sciences	Louvain La Neuve
Ocean Model Pedigree	MOM	POM	POM	Finite Elements	MOM	OPA
Coupled Sea-Ice Model	Yes	Yes	Yes	Yes	Yes	Yes

AOMIP Model ID	NPS	NYU-a	NYU-b	RAS	UW
Home Institute	Naval Postgraduate School	New York University	New York University	Russian Academy of Sciences	University of Washington
Ocean Model Pedigree	MOM	MICOM	MOM	Finite Element	MOM
Coupled Sea-Ice Model	Yes	Yes	Yes	Yes	Yes

Global AOMIP models

AOMIP model ID	**LANL**	**UW**	**NERSC**	**UCL**
Home Institute	Los Alamos National Laboratories	University of Washington	Nansen Environmental and Remote Sensing Center	Universite Catholique de Louvain
Ocean Model Pedigree	POP	POIM	MICOM	OPA
Coupled Sea-Ice Model	Yes	Yes	Yes	Yes

POP – Parallel Ocean Model; MOM - GFDL Modular Ocean Model

POIM – Parallel Ocean Ice Model; MICOM – Miami Isopycnal Ocean Model

POM – Princeton Ocean Module Model;

OPA – Ocean General Circulation modeling System

MODELS: Vertical grid coordinates

code	type	# of levels	min spacing	max spacing
AWI	z	33	10m	356m
GSFC	sigma	20	0.00125	0.2
DRAKKAR	z	46	6m	250m
ICMMG	z	33	10m	500m
LANL	z	40	10m	250m
LU	z	29	10m	290m
NPS	z	30	20m	200m
NYU	layer	11	~ 0.5m *	~ 500m
POL	z	26	5m	500m
FEMAO1	z	16	10m	1000m
FEMAO2	z	33	10m	500m
INMOM	sigma	27	0,0032	0,102
RCO	z	59	3m	200m
UCL	z	31	10m	500m
UW	z	21	10m	790m
IARC-A	z-sigma	25	2m	1000m
IARC-B	z-sigma	25	2m	1000m
ECCO2	z	50	10m	~450m
NOCS/ORCA25	z	64	6 m	204 m
LOCEAN	z (shaved cells)	46	6m	250m
IOS	z	29	10m	290m

code	type	# of nodes	min spacing	max spacing	domain
AWI	B, spherical	= 41310	25.8km	27.8km	50N Atlantic - Bering Str.
GSFC	C, rotated spherical	256x256	0.35	0.45	16S Atlantic - Bering Str.
DRAKKAR	B(ice), C(ocean)	1442 x 1021	5.6 x3.1km	27.8km	global
ICMMG	C, Spherical-bipolar	140 x 180	35 km	1	Atlantic+ Arctic
LANL	B, general curvilinear	900 x 600	9 km	44 km	global
LU	B, rotated spherical	105 x 112	0.5	55km	50N Atlantic - Bering Str.
NERSC	B(ice),C(ocean)	196 x 360	22.2km	270km	global
NPS	B, rotated spherical	384 x 304	1/6	18.5km	50N Atlantic - Bering Str.
NYU	C, rotated spherical	60 x 60	1.0	111km	30N
POL	B, rotated spherical	120 x 129	30km	300km	global
FEMAO1	A, spherical fin. element	35 x 49	1.0	111km	65N Atlantic - Bering Strait
FEMAO2	A, spherical fin. element	307 x 397	1/6º	18.5 km	50N Atlantic to 65N Pacific
INMOM	C, spherical	440 x 620	0.25	0.25	~20S to Aleutian
RCO	B, rotated spherical	152 x 113	0.5	55km	50N to Aleutian
UCL	B(ice),C(ocean) curvilinear	142 x 149	47 km	222km	global
UW	B, rotated spherical	130 x 102	~ 40km	~ 40km	Arctic + GIN Sea
IARC-A	B, rotated spherical	180 x 160	25.6km	27.8km	GIN Sea to Bering St.
ECCO2	C, cube-sphere	420x384	~15km	~22km	Regional Arctic+GIN Sea
ORCA25	C (ocean), B (ice)	1442x1021	6 x3.1 km	27.8 km	global
LOCEAN	B(ice),C(ocean) curvilinear	260*480	~25 km	~50 km	From 50 N Pacific to 30 S Atlantic
IOS	B, rotated spherical	91 x 67	0.5	55km	GIN Sea to Bering Str.

FRICTION

code	vertical	horizontal	bottom
AWI	constant, 10 cm2/s	biharmonic, A4=0.5e-21 cm4/s	quadratic, 1.2e-3
GSFC	Mellor-Yamada 2.5	Smagorinski	quadratic
DRAKKAR	TKE background 1.e-4 m2/s	Biharmonic A4 = 1.2e10 m4/s in the Arctic	Quadratic 1.e-3
ICMMG	constant, 50 cm2/s	neptune	linear
LANL	10 x tracer KPP	biharmonic, A4=1.e20 cm4/s	quadratic, 1.22e-3
LU	neptune, 300 cm2/s	neptune, L=3.5e3 m, A2=5e8 cm2/s	quadratic, 1.2e-3
NERSC	10 x background tracer	laplacian	quadratic
NPS	Pacanowski & Philander	biharmonic, A4=1.e-19 cm4/s	
NYU	interlayer, 1.e-5 m/s2	laplacian, propto grid space	quadratic
POL	KPP + constant 10cm2/s	neptune + Smagorinsky	none
FEMAO1	Constant 10.0 cm2/s, or Monin-Obukhov > 1.0 cm2/s,	Neptune+Laplacian, A2=1.e4 m2/s	quadratic, 1.0e-3
INMOM	Kochergin, Monin, Obukhov, 1 cm2/s	biharmonic, A4~1.e-19 cm4/s	quadratic, 2.5e-3
RCO	k-epsilon (Meier, 2001)	laplacian 5.e3 m2/s	quadratic 1.25e-3
UCL	1.5L turbulence scheme	laplacian, A2=4.e4 m2/s	linear, 115day
UW	constant, 0.05 cm2/s	laplacian, A2=1.2e8 cm2/s	none
IARC-A	constant 1.e-4 m2/s	laplacian, A2=5.e3 m2/s	quadratic, 1.e-3
IARC-B	constant 1.e-4 m2/s	Smagorinsky biharmonic, C=3	quadratic, 1.e-3
ECCO2	5.661e-4 m2/s	modified Leigh (Fox-Kemper & Menemenlis, 2008)	no-slip, quadratic, 2.1e-3
NOCS/ORCA25	TKE+enhanced 1.e-4 m2/s	bi-harmonic (-1.5e-11 m/2s)	quadratic + local enhancement
LOCEAN	Gaspar et al., 1990	biharmonic : -8.5e+11	non-linear
IOS	neptune, up to 1 m2/s	neptune, L=3.5e3 m, A2=4.e4 m2/s	quadratic, 1.2e-3

TIME STEP

code	Types numerical	ocean moment	ocean tracer	sea ice
AWI	LF	900s	900s	900s
GSFC	LF	720s	720s	720s
DRAKKAR	LF+Asselin	1440s	1440s	7200s
ICMMG	split	14400s	14400s	10800s
LANL	LF + F	1800s	1800s	1800s + 15s
LU	LF + PC + F	21600s	21600s	21600s
NERSC	filtered LF	1600s	1600s	1600s*
NPS	LF + F	1200s	1200s	7200s
NYU	filtered LF	7200s + 1200s	7200s	7200s
POL	LF+Asselin+EE+IE	1440s + 239s	43200s	43200s
FEMAO1	IE + EE + PC	7200s	7200s	7200s + 60s
INMOM	IE + PC + F	3600s	3600s	3600s w/ 120 sub-stp.
RCO	LF+EB	600s + 10s	600s	15s
UCL	LF + F	5760s	5760s	17280s
UW	LF	720s	720s	5400s
IARC-A	LF+EB+F	360s + 6s	360s	360s + 36s
IARC-B	LF+EB+F	72s + 1.2s	72s	72s + 7.2s
ECCO2	IE+EE+PC	1200s	1200s	600s
NOCS/ORCA25	LF+Asselin +EE+IE	1440 s	1440 s	7200 s
LOCEAN	LF + Asselin	2160s	2160s	10800s
IOS	LF + F + PC	43200s *	43200s	43200s

LF=leapfrog, PC=predict-correct, F=forward, IE=implicit Euler, EE=explicit Euler

*ice velocities are updated daily

Equation of state

code	source
AWI	3rd oder polynomial fit to Knudsen
GSFC	Mellor, 1991
DRAKKAR	NESCO 1981, Jackett and McDougal 1995
ICMMG	Gill 1982
LANL	UNESCO 1981, Jackett and McDougal 1995
LU	UNESCO 1981
NERSC	Brydon, Sun and Bleck`1999
NPS	UNESCO, Parsons, 1995
NYU	Brydon, Bleck, and Sun, 1999
POL	UNESCO 1983, Jackett and McDougal 1995
FEMAO	Brydon, Bleck, and Sun, 1999
INMOM	Brydon, Sun and Bleck, 1999
RCO	3rd order polynomial fit to UNESCO formula (Bryan and Cox, 1972)
UCL	UNESCO 1983, Jackett and McDougal 1995
UW	Bryan and Cox, 1972
IARC-A	UNESCO 1981
IARC-B	UNESCO 1981
ECCO2	Jackett and McDougal 1995
NOCS/ORCA25	UNESCO 1983, Jackett and McDougal 1995
LOCEAN	UNESCO, Jackett and McDougal 1995
IOS	UNESCO 1981

MIXING

code	vertical	Lateral	convection
AWI	none (see advection)	none (see advection)	complete
DRAKKAR	TKE background 1.e-5 m2/s	Isopycnal laplacian 130 m2/s	High diff., 10 m2/s
ICMMG	Bryan & Lewis, 1979	laplacian, 1000 to 500 m2/s	based on Richardson no.
LANL	KPP, no double diffusion	isopycnal-GM, K=2400 m2/s	high diff., 0.1 m2/s
LU		laplacian, 5e4	complete
NERSC	stability dependent + gravity entrainment	laplacian, prop to grid space	inflating first layer if denser
NPS	Pacanowski & Philander	biharmonic, 4.e18 cm4/s	Semtner, 1974
NYU	McDougal & Dewar, 1998	laplacian, propto grid space	Holland and Jenkins, 2001
POL	KPP + Gargett & Holloway 1984	isopycnal-GM	complete
FEMAO	Constant 1.0 cm2/s, or Monin-Obukhov > 0.01 cm2/s	upwind-streamline +GM	high diff., 0.1 m2/s
INMOM	Kochergin, Monin, Obukhov, 0.05 cm2/s	laplacian at z=const	high diff., 0.1 m2/s
RCO	k-epsilon (Meier, 2001)	laplacian 5.e2 m2/s	k-epsilon (Meier, 2001)
UCL	1.5L turbulence scheme	isopycnal-GM, K=2000 m2/s	enhanced diffusion
UW	constant, 0.05 cm2/s	laplacian, 0.4e6 cm2/s	?
IARC-A	0.1 ~ 3.0 cm2/s	isopycnal-GM, 1.e2 m2/s	complete
ECCO2	KPP, no double diffusion	none (see advection)	high diff. + nonlocal transport, 0.1m2/s
NOCS	TKE	laplacian on isopycnals	TKE
LOCEAN	Gaspar et al., 1990	isoneutral, laplacian, K=500 m2/s	enhanced diffusion
IOS	internal wave & double diffusion (Merryfield et al, 1999)	laplacian, to 500 m2/s	complete

code	ocean tracers	ocean momentum	sea ice & snow
AWI	FCT (Gerdes, Koberle, Willebrand, 1991)	centered difference	corrected upstream (Smolarkiewicz, 1983)
DRAKKAR	TVD (Total Variation Diminishing)	TVD	2nd order (Prather, 1986)
OCMMG	linear FE	upstream viscosity	upstream + remap
LANL	3rd order upwind	centered difference	incremental remapping
LU	modified Prather SOM	centered difference	modified Prather SOM
NERSC	MPDATA (Smolarkiwicz, 1984)	PV-conserving (Sadourny, 1975)	3rd order (Jiang & Shu, 1996)
NPS	centered difference	centered difference	centered difference
NYU	MPDATA (Smolarkiwicz, 1984)	PV-conserving (Sadourny)	MPDATA. (Smolarkiwicz, 1984)
POL	modified Prather (1986)	centered difference	modified Prather (1986)
FEMAO	upwind streamline	FE scheme	upwind streamline
INMOM	centered 2nd order	centered 2nd order	upwind
RCO	modified QUICK (Webb et al., 1998)	modified QUICK	upstream
UCL	centered 2nd order	centered 2nd order	2nd order moments (Prather, 1986)
UW	centered difference	centered difference	centered difference
IARC-A	UTOPIA + QUICKEST	centered difference	weighted upstream
ECCO2	7th order monotonicity-preserving [Daru and Tenaud, 2004]	vector invariant	centered 2nd order
ORCA-25	TVD	Energy-enstrophy conserving	2nd order (Prather, 1986)
LOCEAN	centered 2nd order + TVD scheme	centered 2nd order	2nd order (Prather, 1986)
IOS	modified Prather (1986)	centered difference	modified Prather (Merryfield & Holloway, 2002)

ADVECTION

Sea ice dynamics

code	variables	ice dynamics
AWI	area fractions in 7 thickness bins	viscous plastic
GSFC	area & thickness	general viscous
DRAKKAR	Snow and ice area & thickness, energy, Concentration.	Viscous plastic
ICMMG	area fractions in 5 thickness bins	elastic-viscous-plastic
LANL	area fractions in 5 thickness bins*, ice energy, snow energy	elastic-viscous-plastic
LU	area, thickness	viscous plastic
NERSC	area & thickness, age	viscous plastic
NPS	area & thickness	viscous plastic
NYU	area & thickness, age	cavitating fluid
POL	snow & ice area, volume, heat & age	elastic-viscous-plastic
FEMAO	ice and snow mass in 14 thickness bins	elastic-viscous-plastic
INMOM	ice and snow mass, area	elastic-viscous-plastic
RCO	area & thickness	elastic-viscous-plastic
UCL	area & thickness, energy, brine	viscous plastic
UW	area & thickness, ice enthalpy, distrib?	viscous plastic
IARC-A	area & thickness	elastic-viscous-plastic
ECCO2	area, thickness, salt, snow	viscous plastic
ORCA25	sea ice area, thickness, snow depth, brine, energy	viscous-plastic
LOCEAN	area & thickness, energy, brine	viscous plastic
IOS	area, thickness	viscous plastic

Sea ice thermodynamics

code	ice T profile	ice conductivity	ice salinity	snow T profile	snow conductivity
GSFC	linear	2.04 W/m/K	5 ppt	linear	0.31 W/m/K
DRAKKAR	2 layers	2.03 W/m/K	6 ppt	linear	0.22 W/m/K
ICMMG	4 layers	2.03 W/m/K	function	linear	0.3 W/m/K
LANL	4 layers	2.03 W/m/K	function	linear	0.3 W/m/K
LU	linear	2.04 W/m/K	4 ppt	linear	0.31 W/m/K
NERSC	linear	2.04 W/m/K	6 ppt	linear	0.31 W/m/K
POL	parabolic	2.03 W/m/K	4 psu	parabolic	0.22 W/m/K
FEMAO	linear	2.04 W/m/K	4 ppt	linear	0.31 W/m/K
INMOM	linear	2.04 W/m/K	4 ppt	linear	0.31 W/m/K
RCO	2-layer model	2.0 W/m/K	4 ppt	linear	0.3 W/m/K
UCL	2 layers	2.03 W/m/K	4 ppt	linear	0.22 W/m/K
UW	?	?	4 ppt	?	0.31 W/m/K
IARC-A	linear	2.04 W/m/K	5 psu	linear	0.31 W/m/K
ECCO2	linear	2.17 W/m/K	function	linear	0.31 W/m/K
NOCS/ORCA25	2-layer linear	2.03 W/m/K	4 ppt	linear	0.31 W/m/K
LOCEAN	2 level ice	2.03 W/m/K	6 ppt	linear	0.22 W/m/K
IOS	linear	2.04 W/m/K	4 ppt	linear	0.31 W/m/K

Atmosphere – ocean exchange

code	Heat exchange	Moisture exchange	Momentum transfer	Ocean mixed layer?
DRAKKAR	Large and Yeager, 2004	Bulk CORE	Bulk CORE	TKE
GSFC	bulk	bulk	bulk	turbulence scheme
ICMMG	Bulk	bulk	bulk	integral Ri criterion
LANL	bulk	bulk	bulk	KPP
LU	bulk	bulk	assigned	none
NYU	Bulk (Oberhuber, 1993)	bulk	bulk	bulk (Gaspar, 1988)
POL	bulk (Large and Pond 1982)	bulk (Large and Pond 1982)	bulk (Large and Pond 1981)	KPP
FEMAO	1.2e-3 for stable atm. 1.75e-3 for unstable	1.5e-3 for stable atm. 1.75e-3 for unstable	Quadratic 1.1+.04*wind	turbulence scheme
INMOM	bulk	bulk	bulk	5m
RCO	bulk (Large and Pond 1982)	bulk (Large and Pond 1982)	bulk (Large and Pond 1981)	included in k-epsilon
UCL	bulk	bulk	bulk	1.5L turbulence scheme
UW				bulk (Zhang et al, 1998)
IARC-A&B	bulk	bulk	assigned	Noh and Kim (1999)
ECCO2	bulk (Large and Yeager)	bulk (Large and Yeager)	bulk (Large and Yeager)	KPP
ORCA25	bulk	bulk	bulk	TKE
LOCEAN	bulk (Large and Yeager)	bulk (Large and Yeager)	prescribed daily wind stress (ERA 40)	
IOS	1.2e-3	1.5e-3	assigned	assigned

Ocean - ice exchange

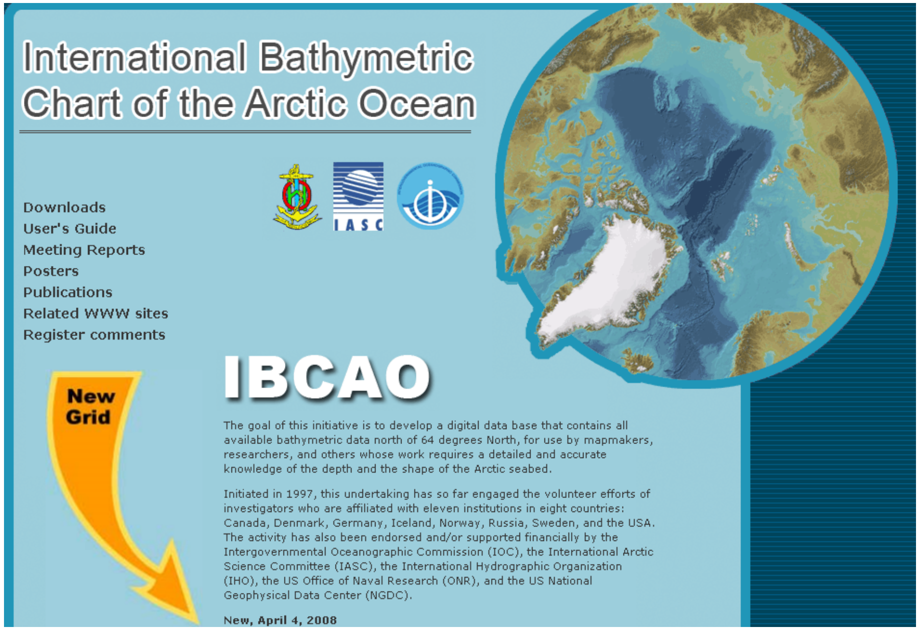
code	Ocean-ice heat	Ocean-ice FW	Ocean-ice moment.
DRAKKAR	linear in ocean T - freezing T	salt rejection, freshwater flux, ice at 6 ppt	quadratic, 5.5e-3
GSFC	Boundary layer model (Mellor and Kantha, JGR 1989)	Same	same
ICMMG	same as LANL	same as LANL	same as LANL
LANL		virtual salt flux, ice at 4 ppt	quadratic, 5.5e-3
LU	linear in ocean T - freezing T	virtual salt flux, ice at 4 ppt	quadratic, 5.5e-3
NERSC	linear in To and Tf (Maykut and McPhee, 1995)	virtual salt flux, ice at 6ppt	quadratic, 5.5e-3
NPS			quadratic, 5.5e-3
POL	linear in To and Tf (McPhee, 1992)	explicit freshwater and salt	quadratic, .5e-3
FEMAO	linear in To and Tf (McPhee, 1992)	explicit freshwater and salt, ice at 4 ppt	quadratic, 5.5e-3+ Gravity wave drag
INMOM	Ebert & Curry, 1993		quadratic, 5.5e-3
RCO	bulk (Omstedt & Wettlaufer, 1992)	salt rejection, freshwater flux, ice at 4 ppt	quadratic, 3.5e-3
UCL	linear in ocean T - freezing T	salt rejection, freshwater flux	quadratic, 5.5e-3
IARC-A	reset SST to freezing T	salt rejection, freshwater flux	quadratic, 5.e-3
IARC-B	reset SST to freezing T	salt rejection, freshwater flux	quadratic, 5.e-3
ECCO2	relax SST to freezing T	explicit salt exchange (Nguyen et al, 2009)	quadratic, Cd=5.56e-3
ORCA25	Turbulent mixing (McPhee, 1992)+lead model	freshwater and salt	quadratic, 5.0e-3
LOCEAN	linear in ocean T - freezing T	salt rejection	Hibler and Bryan, 1987
IOS	linear in ocean T - freezing T	virtual salt flux, ice at 4 ppt	quadratic, 5.5e-3

Radiation

code	SW form	albedo	SW pen.	LW form
DRAKKAR	Daily	O=.1, MI=.5, I=.6, MS=.7, S=.8	+	Separate up & down
GSFC	Parkinson and Washington, 1979	O=0.1, I=0.68, S=0.85, linear between S and I for surface temperatures above 10C	-	separate up & down, PW
ICMMG	daily	O=.1, MI=.68, I=.7, MS=.77, S=.81	+	Rosati & Miyakoda, 1988
LANL		O=.1, MI=.68, I=.7, MS=.77, S=.81	+	Rosati & Miyakoda, 1988
LU	daily	O=.1, MI=.5, I=.6, MS=.7, S=.8	+	Rosati & Miyakoda, 1988
NYU	daily	O=.1, MI=.4, I=.5, MS=.7, S=.8		Holland, 1993
POL	daily averaged, Zillman (1972), Shine (1984)]	O=.1, MI=.5, I=.6, MS=.7, S=.8	+	net (Berliand & Berliand, 1952)
FEMAO	daily cycle Zillman (1972)	O=.1, MI=.65 -0.075*(T+1.) (T>-1), I=.65, MS = 0.80 -0.1*(T+1.0) (T>-1), S=.8	+	Rosati & Miyakoda, 1988
INMOM	daily	O=0.1, MI=0.5, I=0.6 , MS=0.7, S=0.8		
RCO	daily cycle, Bodin (1979)	O=Fresnel, MI=0.3, I=0.7, MS=0.77, S=0.87	+	Maykut and Church (1973)
UCL	daily	O=.1, MI=.5, I=.6, MS=.7, S=.8	+	separate up & down
IARC-A	Parkinson and Washington (1979)	O=.1, MI=.5, I=.6, MS=.8, S=.8	+	Rosati & Miyakoda, 1988
ECCO2	6-hourly	O=0.16, MI=0.71, I=0.7, MS=0.81, S=0.87	+	separate up & down
ORCA25	daily	Grenfell & Perovich, 1984; Payne, 1972; Shine & Hendersson-Sellers	+	separate up and down LW
IOS	daily	O=.1, MI=.5, I=.6, MS=.7, S=.8	yes	Rosati & Miyakoda, 1988

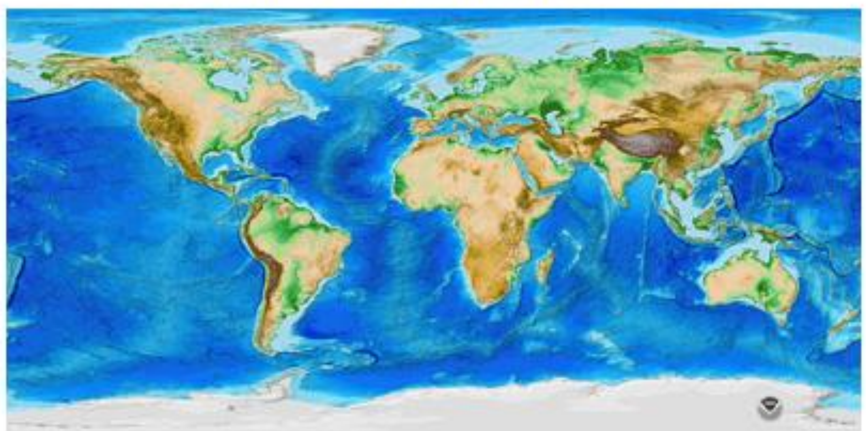
DATA for models:

To ensure an accurate intercomparison experiment, and to eliminate problems in interpretation of model results, it was decided to force and validate all models in as similar a manner as possible. To this end, we have collected and created a variety of standardized model forcing data sets:



For bathymetry, we have created a global merged data product that blends the International Bathymetric Chart of the Arctic Ocean data with the Earth Topography One Minute data (Holland, 2000).

ETOPO1 Global Relief Model

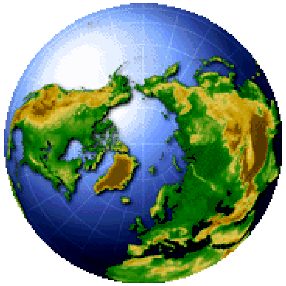


ETOPO1 is a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry. It was built from numerous global and regional data sets, and is available in "Ice Surface" (top of Antarctic and Greenland ice sheets) and "Bedrock" (base of the ice sheets) versions. Historic ETOPO2v2 and ETOPO5 global relief grids are deprecated but still available.

Welcome to

R-ArcticNET

(Draft v4.0)



A Regional, Electronic, Hydrographic Data Network For the

R-ArcticNET Abstract and Background

Enter R-ArcticNET Geographically Referenced Database

Direct Link to the Datafiles

Russian Daily Discharge Data from NSF-funded UCLA/UNH project

ART-Russia River Temperature Data

R-Arcticnet V3.0

For **river-runoff**, we will be using the hydrographic data product for the arctic region developed at the University of New Hampshire (Lammers et al., 2000).

http://www.r-arcticnet.sr.unh.edu/v4.0/index.html

Marine Biological Laboratory

Canada

Environment Canada

USGS science for a changing world

NASA

CHAMMP

Data

Forcing Data Notation

Atmospheric Forcing Data

Hydrographic Forcing Data

Surface-Restoring Forcing Data

River-Runoff Forcing Data

Sea-Ice Forcing Data

Topographic Forcing Data

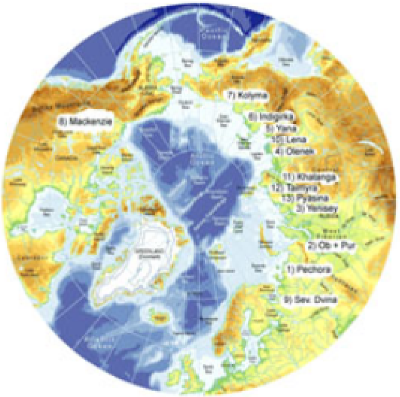
100-Year Run Atmospheric Forcing Data

Validation Data - WSC Moorings

River-Runoff Forcing Data

ShareThis Email Print PDF

The river-runoff forcing data set is a climatology from AWI (Prange, 2001, 2002) which is based on raw data from the Global River Data Center (GRDC) in Koblenz, Germany. The data set contains monthly runoff for thirteen major arctic rivers. The river names and locations are illustrated on a map.



Enlarge Image

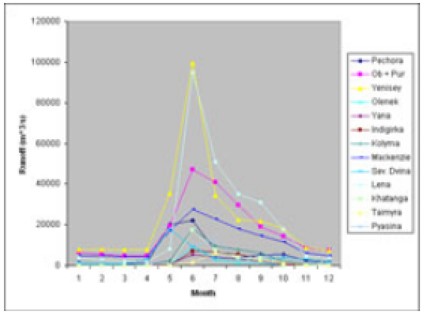
Names and locations of the thirteen major arctic rivers.

R-ArcticNET

The Global Runoff Data Center (GRDC) provides river discharge data for all major rivers of the world. Using that database and other sources, Lammers et al. (2000) have put together a hydrological database for river runoffs into the Arctic Ocean. Spatially, their database covers the entire AOMIP-Grid domain and temporally spans most of the current century. The product is known as R-ArcticNET.

AWI

In an analogous fashion, Prange (2002) at the AWI has put together a data base of arctic river runoff. That database has been chosen for intial use in the AOMIP coordinated experiment.



Enlarge Image

AWI Total Runoff (m^3 s^{-1})

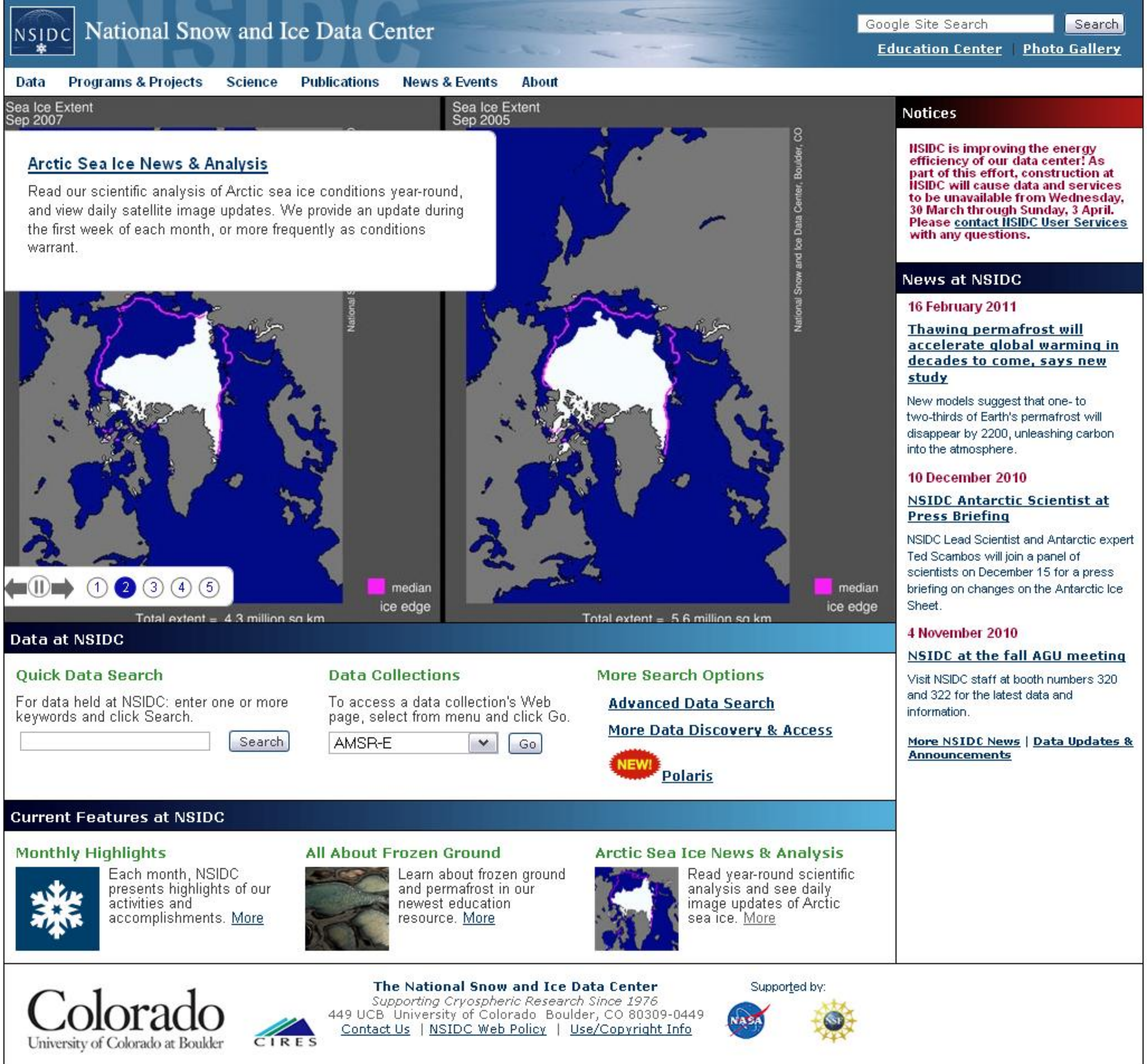
Related Links

- Comparison of Precipitation and River Discharge Data (DWD, ACSYS)
- Composite Runoff Fields V1.0 (UNH/GRDC)
- Global Runoff Data Center (GRDC, Koblenz-Berlin)
- Graham Global Watersheds (NGDC/NOAA)
- Influence of Arctic River Runoff (AWI, Bremerhaven)
- Ocean Model Intercomparison Project - River Forcing (OMIP)
- R-ArcticNET V2.0 (Univ. New Hampshire)
- Total Runoff Integrating Pathways (TRIP, Univ. Tokyo)

Gauged Volume Flux

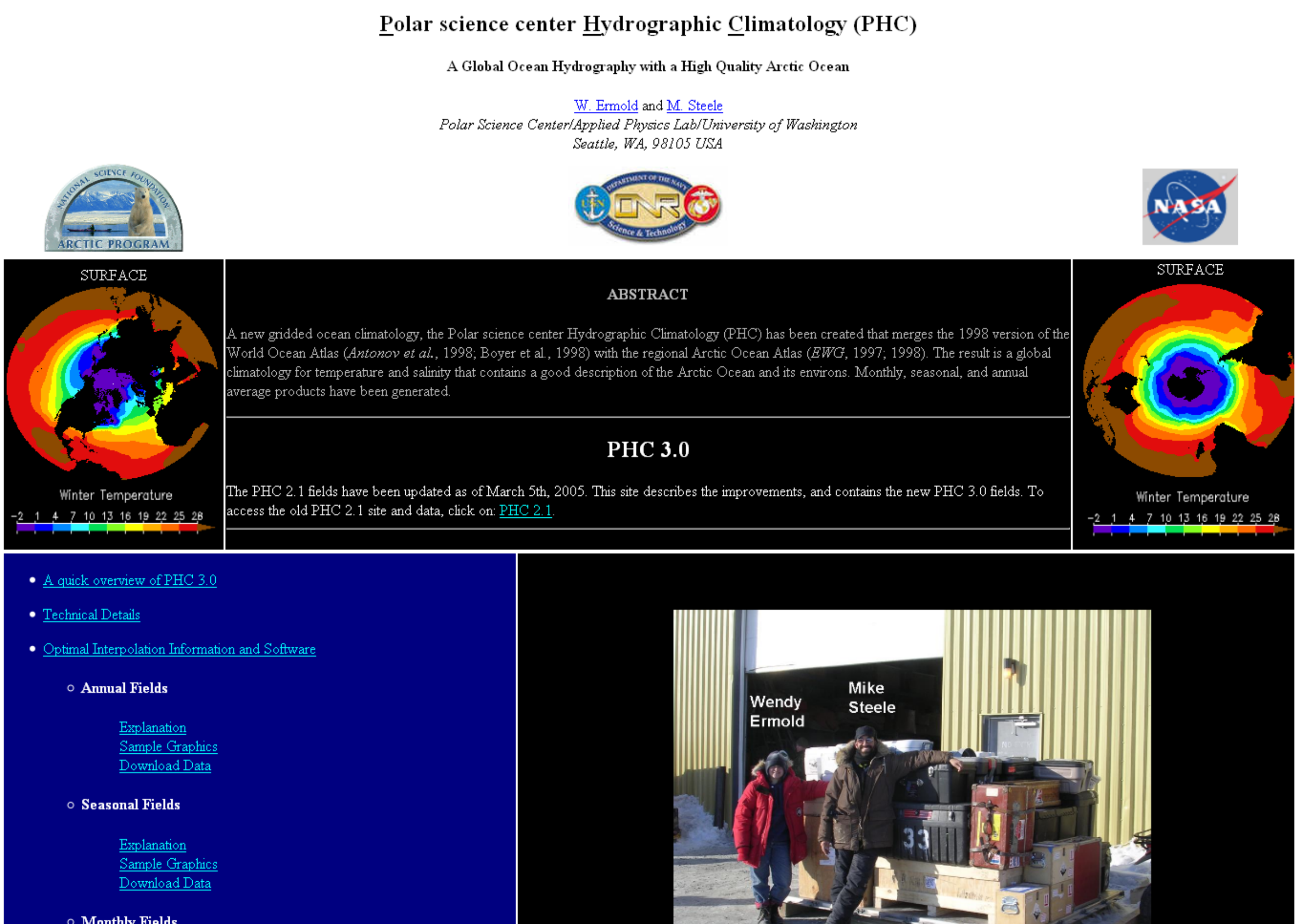
The annual gauged volume flux is 2456 km^3 a^{-1}. The spatial and temporal variation of this flux in units of m^3 s^{-1} is given in a table. To convert the values in the table to units of km^3 a^{-1} multiply by 0.0315.

Index	River	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Pechora	959.400	773.800	695.400	950.200	15502.6	17126.4	5534.20	3227.80	3917.00	4197.60	1894.40	1277.40
2	Ob + Pur	4986.72	4120.23	3635.81	3697.96	15122.7	36715.9	31694.8	23122.7	14747.4	11000.7	6695.36	5734.18



For sea-ice we have used data sets archived at the National Snow and Ice Data Center (NSIDC).

For hydrography, we have produced a global merged data product , where various high-quality Arctic Ocean data sets have been blended with the World Ocean Atlas (Steele et al., 2001).



Polar science center Hydrographic Climatology (PHC)

A Global Ocean Hydrography with a High Quality Arctic Ocean

W. Ermold and M. Steele
Polar Science Center/Applied Physics Lab/University of Washington
Seattle, WA, 98105 USA

SURFACE

Winter Temperature

-2 1 4 7 10 13 16 19 22 25 28

ABSTRACT

A new gridded ocean climatology, the Polar science center Hydrographic Climatology (PHC) has been created that merges the 1998 version of the World Ocean Atlas (*Antonov et al.*, 1998; Boyer et al., 1998) with the regional Arctic Ocean Atlas (*EWG*, 1997; 1998). The result is a global climatology for temperature and salinity that contains a good description of the Arctic Ocean and its environs. Monthly, seasonal, and annual average products have been generated.

PHC 3.0

The PHC 2.1 fields have been updated as of March 5th, 2005. This site describes the improvements, and contains the new PHC 3.0 fields. To access the old PHC 2.1 site and data, click on: PHC 2.1.

SURFACE

Winter Temperature

-2 1 4 7 10 13 16 19 22 25 28

- A quick overview of PHC 3.0
- Technical Details
- Optimal Interpolation Information and Software
  - **Annual Fields**

    Explanation
    Sample Graphics
    Download Data
  - **Seasonal Fields**

    Explanation
    Sample Graphics
    Download Data
  - **Monthly Fields**

Wendy Ermold

Mike Steele

Data

Forcing Data Notation

Atmospheric Forcing Data

Hydrographic Forcing Data

Surface-Restoring Forcing Data

River-Runoff Forcing Data

Sea-Ice Forcing Data

Topographic Forcing Data

100-Year Run Atmospheric Forcing Data

Validation Data - WSC Moorings

Hydrographic Forcing Data

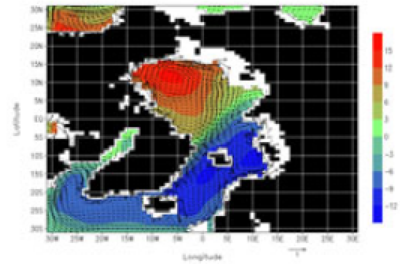
ShareThis Email Print PDF

We are using the Polar Science Center Hydrographic Climatology (PHC) Atlas to initialize the 3-D hydrographic properties of each of the various AOMIP ocean domains. This is a global ocean hydrographic data set with a high-quality representation of the Arctic Ocean.

The PHC atlas will be utilized to initialize the AOMIP models by interpolating the winter-season (i.e., March, April, May) PHC data to each of the model domains. This winter-season salinity and temperature data are available by clicking on the link to the right.

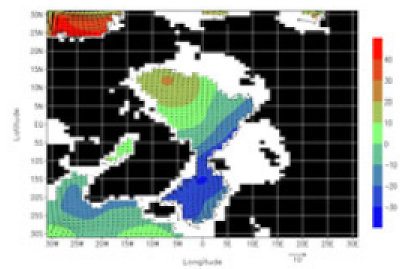
Another use of the PHC atlas is the surface-restoring of salinity.

The Arctic Ocean database for hydrography and circulation has been, until recently, sparse in temporal and spatial coverage. Currently, however, this database has expanded considerably. First, historical hydrographic data have been declassified and released by both Russian and western sources to produce smoothed, three-dimensional grided fields for summer and winter (EWG, 1997, 1998). Secondly, there has been an explosion of cruise data over the past decade. There has been at least one major expedition into the deep Arctic Ocean nearly every year during this period, either by icebreaker or submarine. There have also been data collected by satellites, staffed ice camps and by drifting and bottom-moored buoys, and by tide-gauge stations (Proshutinsky et al., 2001). While Arctic Ocean models have made some use of these data to perform a preliminary validation of models, there has not been until AOMIP an organized, comprehensive validation effort.



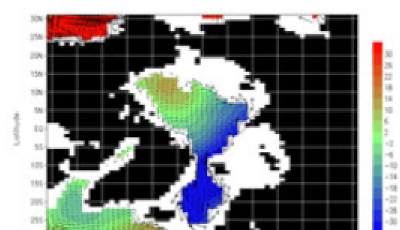
Enlarge Image

Geopotential height 100m



Enlarge Image

Geopotential height 500m



Hydrography

A convenient hydrographic data set for Arctic Ocean modeling is the Polar Hydrographic Climatology (PHC) produced by the Polar Science Center (PSC) at the University of Washington. This data set is a merger of two data sets: (i) the World Ocean Atlas (WOA98) produced by the Ocean Climate Laboratory at the National Oceangraphic Data Center (NODC) and (ii) the Environmental Working Group Atlas (EWG) which is made available through the National Snow and Ice Data Center (NSIDC).

The PHC merged product has the same resolution as the original WOA98, namely a one degree horizontal grid spacing and 33 fixed vertical levels. The PHC data set contains annually-averaged, seasonal, and monthly data files. The annually-averaged and seasonal data span the full depth of the water column, i.e., from 0 m at the surface down to a maximum depth of 5500 m; the monthly data spans only the top 1000 m of the water column. The data are in WOA98 format (i.e., ASCII) with values over land grid points set as "missing".

For atmospheric forcing, we have used derived reanalysis products from the National Centers for Environmental Protection (NCEP).

U.S. Department of Commerce | National Oceanic & Atmospheric Administration | NOAA Research

Earth System Research Laboratory

Serving Society through Science

Search PSD: Search

Calendar | People | Publications

About Research Outreach News Planning Home

Climate Datasets: By Category

- All
- Sub-daily
- Daily
- Monthly
- Surface
- Multi-level
- Land
- Ocean
- Radiation
- Arctic
- Reanalysis
- Climate Indices
- Search Datasets

New Datasets

- 20th Century Reanalysis

Popular Datasets

NCEP/NCAR Reanalysis 1: Summary

Go To: Temporal Coverage | Spatial Coverage | Levels | Update Schedule | Download/Plot Data | Restrictions | Details | Caveats | File Naming | Citation | References | Original Source | Contact

One-Line Description:

- NCEP/NCAR Reanalysis 1

Temporal Coverage:

- 4-times daily, daily and monthly values for 1948/01/01 to present
- Long term monthly means, derived from data for years 1968 - 1996

Spatial Coverage:

- Global Grids

Levels:

- 17 Pressure level and 28 sigma levels. N/A

Update Schedule:

- Daily

Atmospheric Forcing Data

ShareThis Email Print PDF

A variety of atmospheric data sets are available for forcing the AOMIP sea-ice and ocean models. The atmospheric forcing data sets are as follows:

Last updated: March 5, 2010

Surface-Restoring Forcing Data

Restoring of surface salinity is carried out during the coordinated-spinup (Expt. #2) and coordinated-analysis experiments (Expt. #3); there is no restoring of surface temperature. The following strategy has been adopted in an effort to minimize the impact of surface-salinity restoring on the experiments.

During the first eleven years of the integration (i.e., Jan 1948 - Dec 1958) surface restoring is applied everywhere on the ocean surface using a restoring time-scale of 180 days. During the remaining years (i.e., 1959 - forward) there is no restoring of surface salinity. The restoring is performed using an annually averaged climatology of surface salinity from the Polar Science Center Hydrographic Climatology (PHC) atlas.

As an exception to this rule, global-domain models may continue to perform surface restoring of salinity after January 1959, but only in that part of their domains south of 60°N.

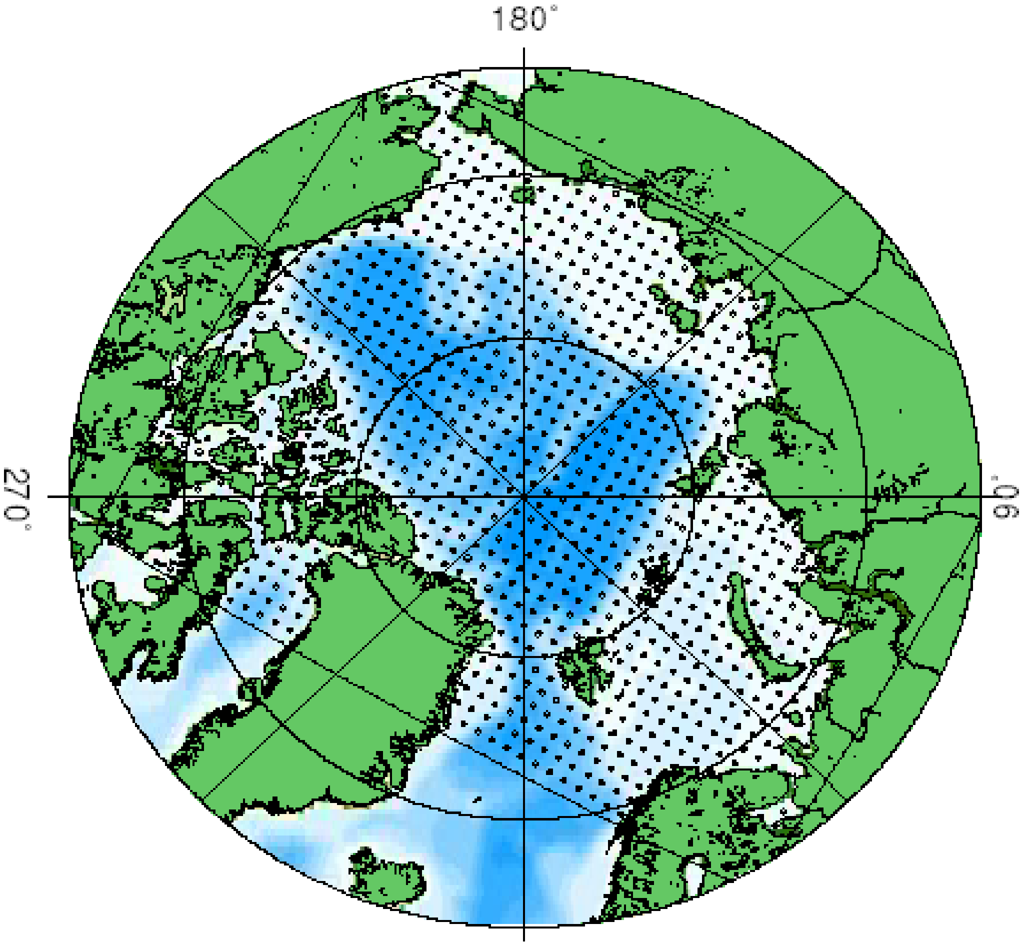
Restoring is also applied along the lateral boundaries of the regional AOMIP domains. The detailed specification on that restoring is the free-choice of the individual AOMIP modeling groups.

Related Files

» Surface Temperature and Salinity (Annual Climatology)
The restoring is performed using an annually averaged climatology of surface salinity from the Polar Science Center Hydrographic Climatology (PHC) atlas.

Last updated: March 5, 2010

Common model domain



The AOMIP grid is defined over a geographic domain that includes the Arctic Ocean, the Bering Strait, the Canadian Arctic Archipelago, the Fram Strait and the Greenland, Iceland, and Norwegian Seas.

VALIDATION: validation of forcing and validation of model results

a) Validation of forcing data

This is mainly validation of atmospheric forcing data derived from reanalysis data. Validation of forcing is needed in order to evaluate uncertainties in model results associated with biases in the model forcing.

Model sensitivity to forcing errors is also one of important directions of AOMIP studies

Atmospheric forcing validation for modeling the central Arctic

(Makshtas, A., D. Atkinson, M. Kulakov, S. Shutilin, R. Krishfield, and A. Proshutinsky (2007), Geophys. Res. Lett. , 34)

Daily data from the NCEP/NCAR "Reanalysis 1" project were compared with observational data obtained from the North Pole drifting stations in order to validate the atmospheric forcing data used in coupled ice-ocean models.

This analysis was conducted to assess the role of errors associated with model forcing before performing model verifications against observed ocean variables.

This analysis showed an excellent agreement between observed and reanalysis sea level pressures and a relatively good correlation between observed and reanalysis surface winds.

The observed temperature is in good agreement with reanalysis data only in winter.

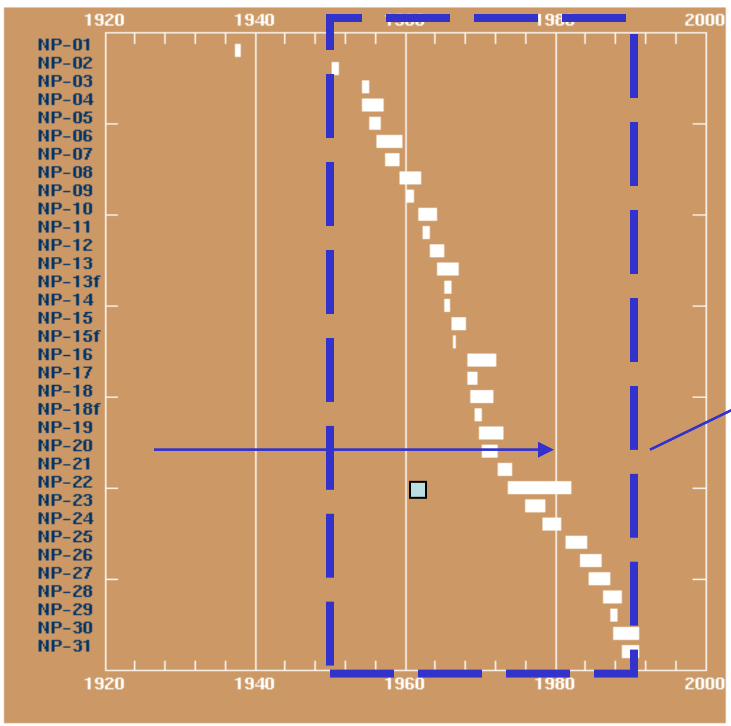
Specific air humidity and cloudiness are not reproduced well by reanalysis and are not recommended for model forcing

Model forcing validation:

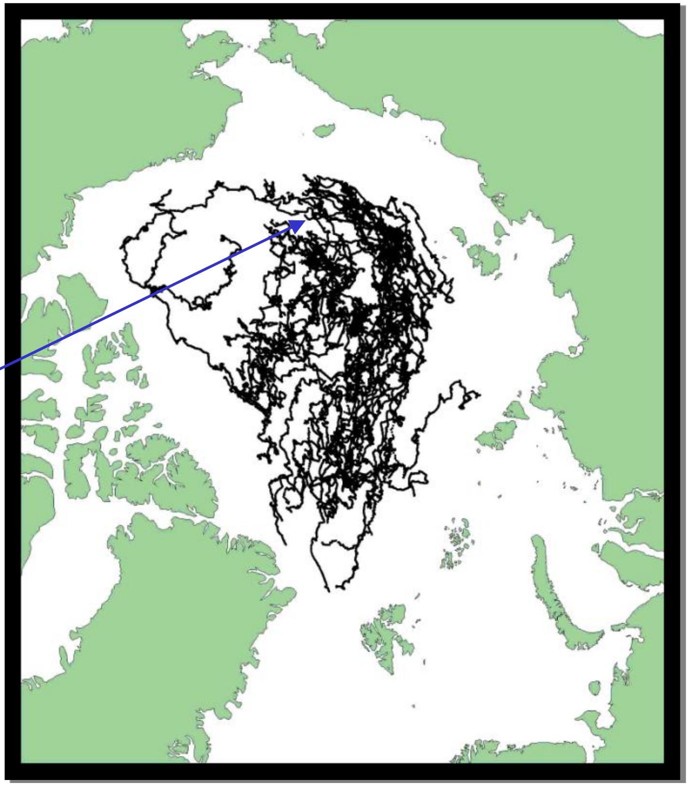
2m air temperature, humidity, wind, SLP, cloudiness from NCAR/NCEP versus North Pole stations

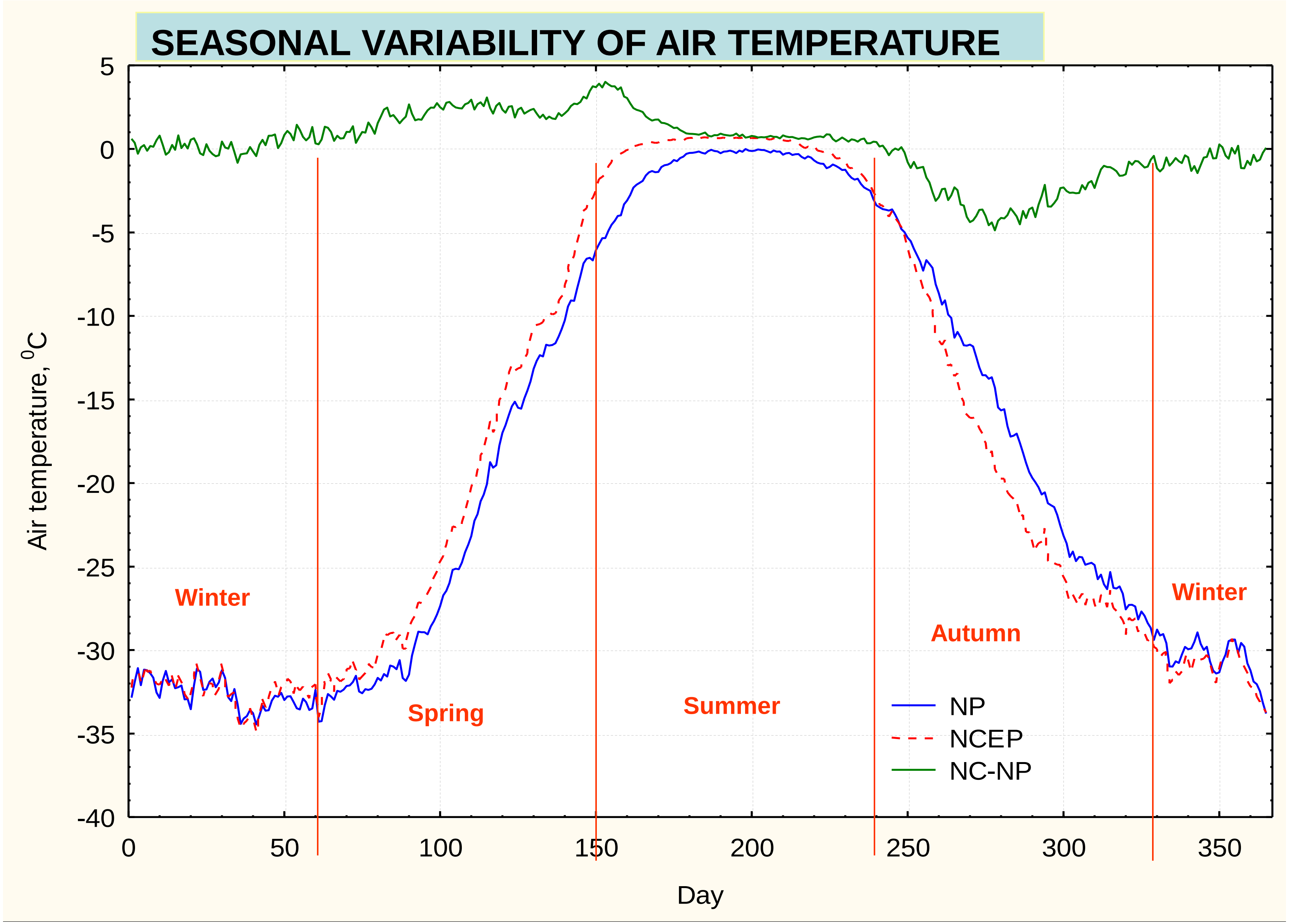
Data Coverage: 1954-1991 and 2003-2006

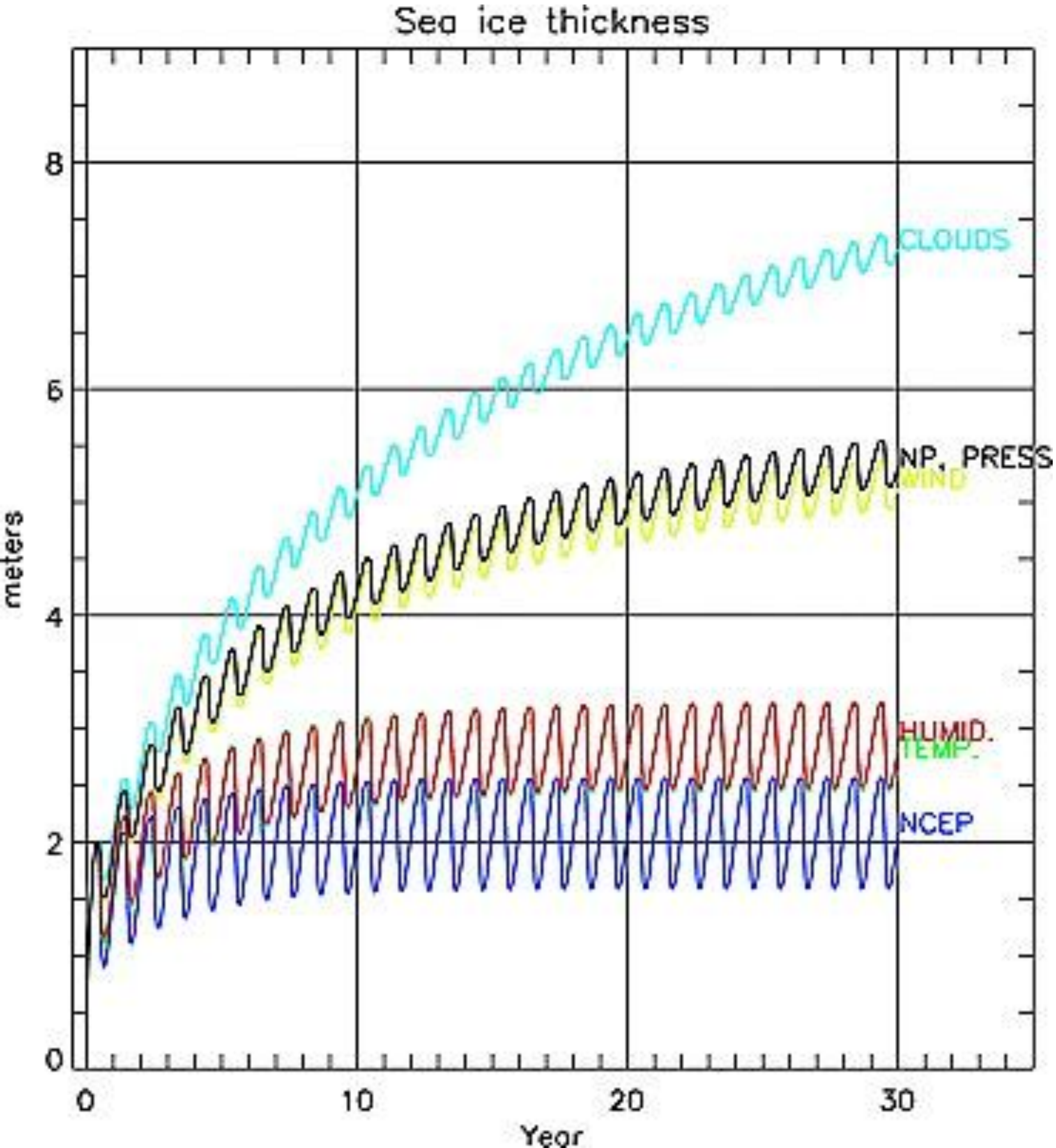
Temporal



Spatial




SEASONAL VARIABILITY OF AIR TEMPERATURE
Air temperature, ^{0}C
Day
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0
50
100
150
200
250
300
350
Winter
Spring
Summer
Autumn
Winter
NP
NCEP
NC-NP



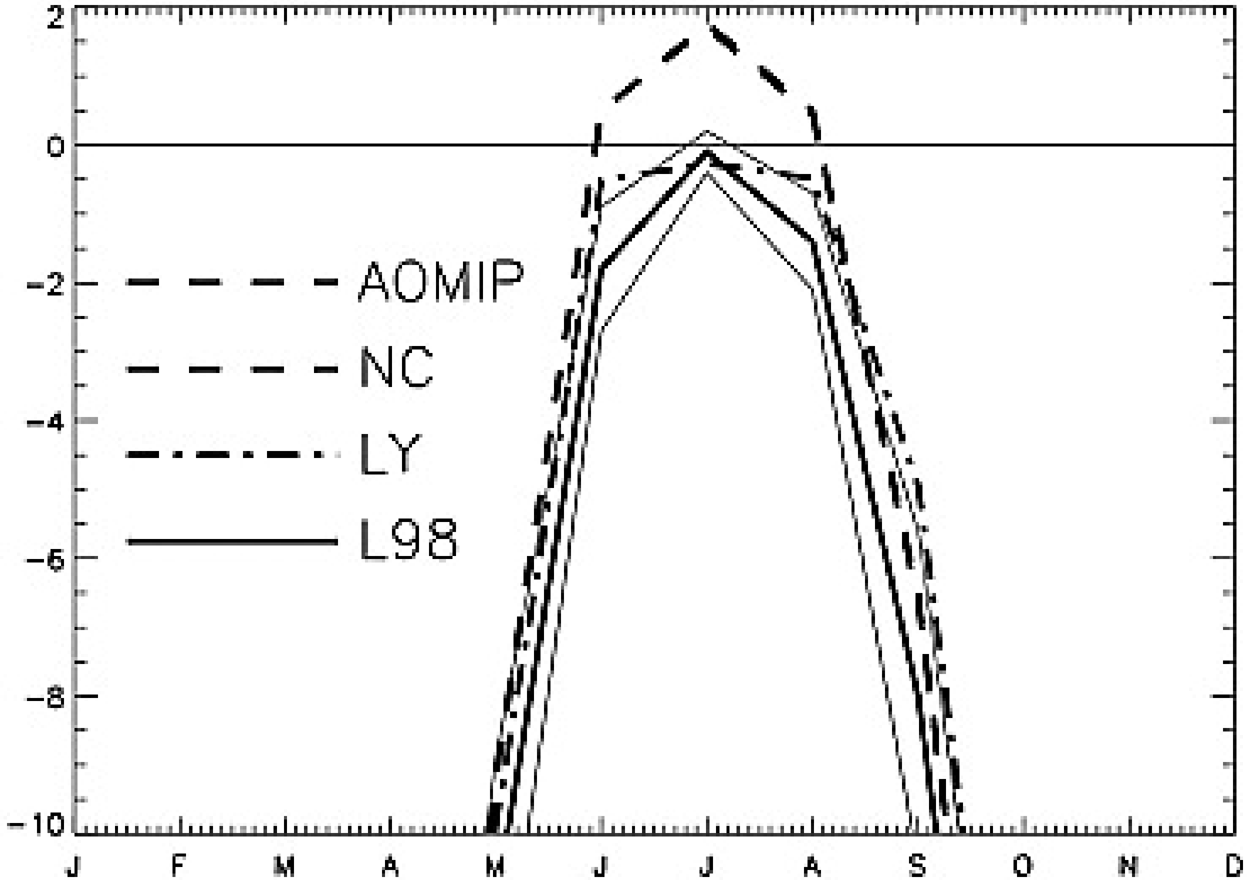
30-year time series of simulated sea ice thickness. Lines depict thickness variability under NCEP and under NP forcing only (NP), under NP forcing using NCEP wind (WIND), NP forcing using NCEP SAT (TEMP.), NP forcing using NCEP specific humidity (HUMID.), and NP forcing using NCEP clouds (CLOUDS).

Global atmospheric forcing data for Arctic modeling

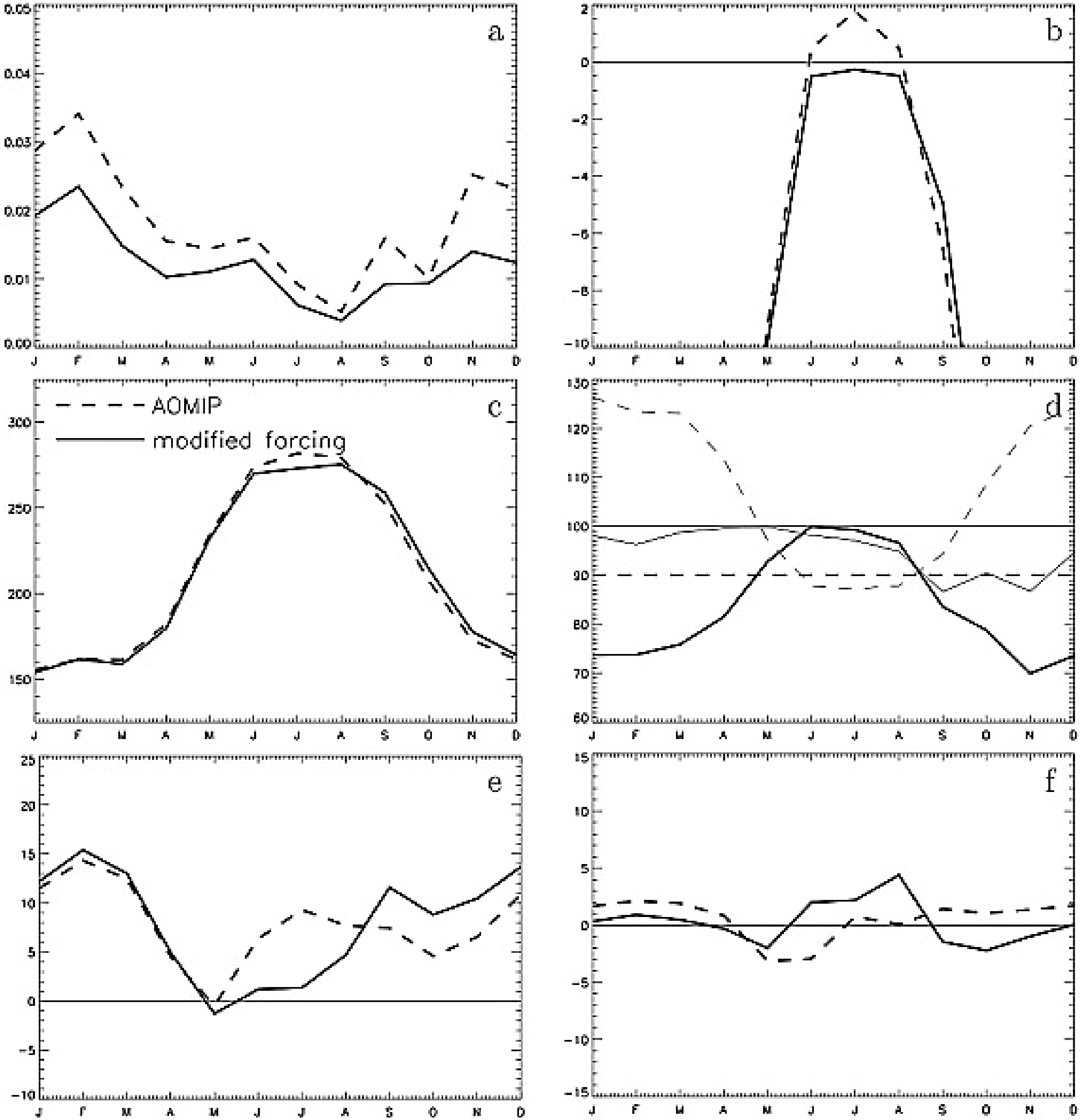
Elizabeth Hunke and Marika Holland [2007] compared three forcing sets:

- **the standard AOMIP protocol;**
- **the standard NCEP forcing fields; and**
- **the data set of Large and Yeager (2004): LY04**

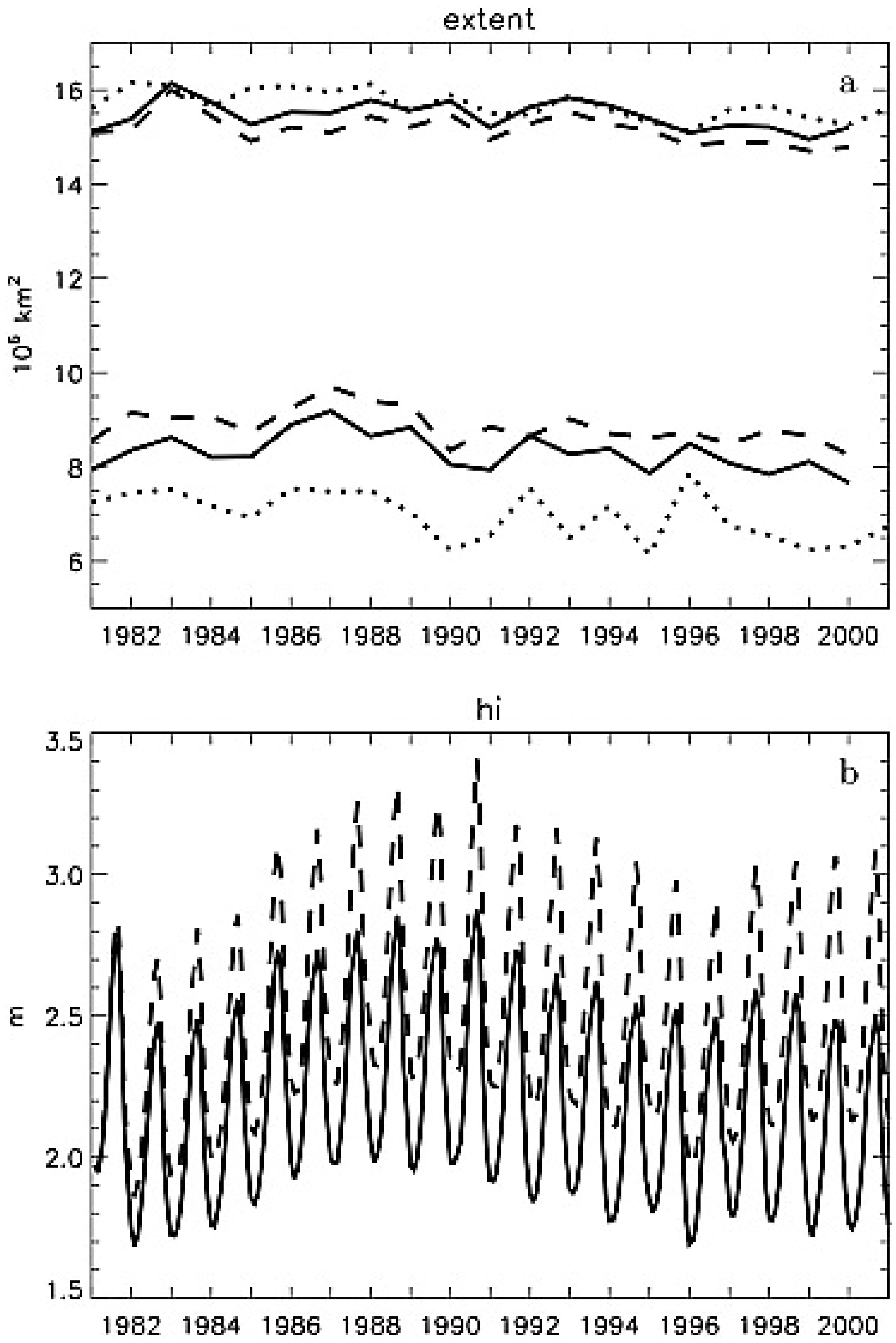
They explored their performance in Arctic simulations using a global, coupled, sea ice-ocean model, and found that while these forcing data sets have many similarities, the resulting simulations present significant differences, most notably in ice thickness and ocean circulation.



Summer 1982 air temperatures, averaged over the Arctic, from AOMIP and NCEP (2 m, identical), LY04 (10 m) and Lindsay [1998] estimates from Russian drifting ice stations with standard deviations (2 m). “NC” and “LY” are labels for our NCEP- and LY04-based experiments



a - Wind stress (N m^{-2})
b - temperature (°C),
c - longwave radiation (W m^{-2}),
d - relative humidity (%),
e - sensible heat flux (W m^{-2})
f - latent heat flux (W m^{-2}) for 1982, averaged over the Arctic



(a) Maximum and minimum monthly average sea ice extent and

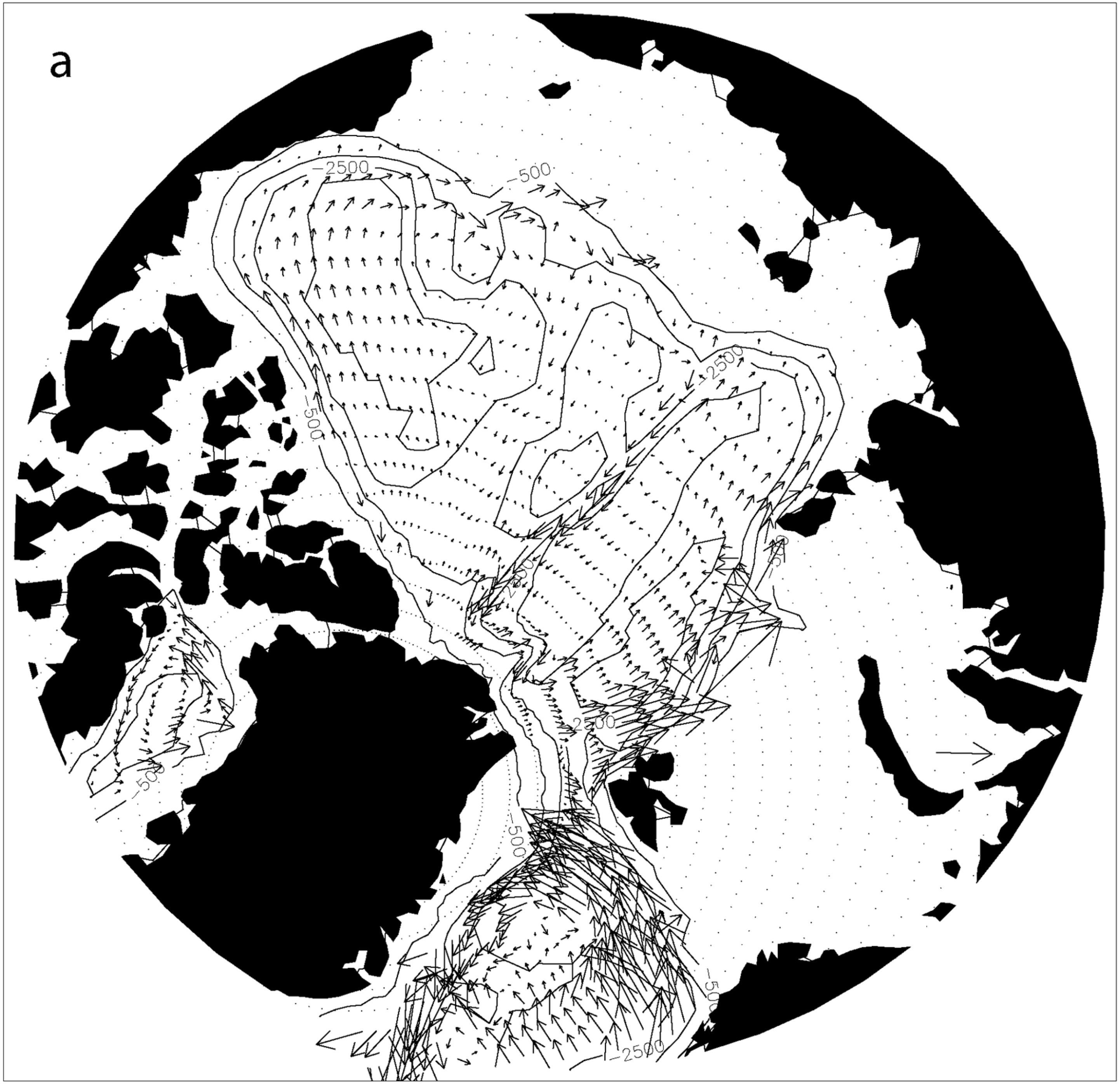
(b) average ice thickness

AOMIP - dashed

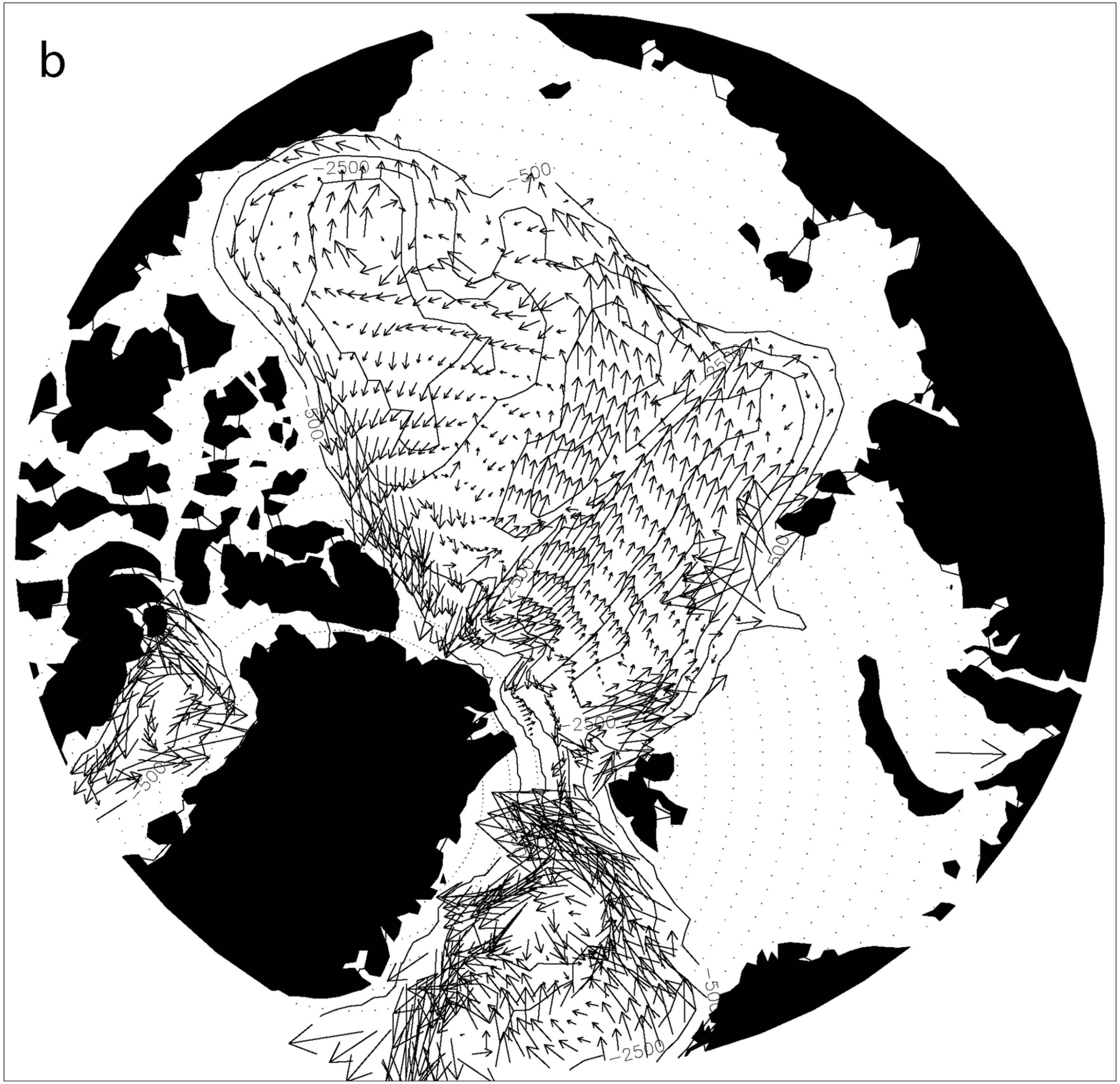
modified forcing – solid

Simulations, for the Northern Hemisphere, from the 1° runs.

Dotted lines in (a) show September and March ice extent from satellite passive microwave data [Fetterer and Knowles, 2002]



Ocean currents at 466 m with modified forcing



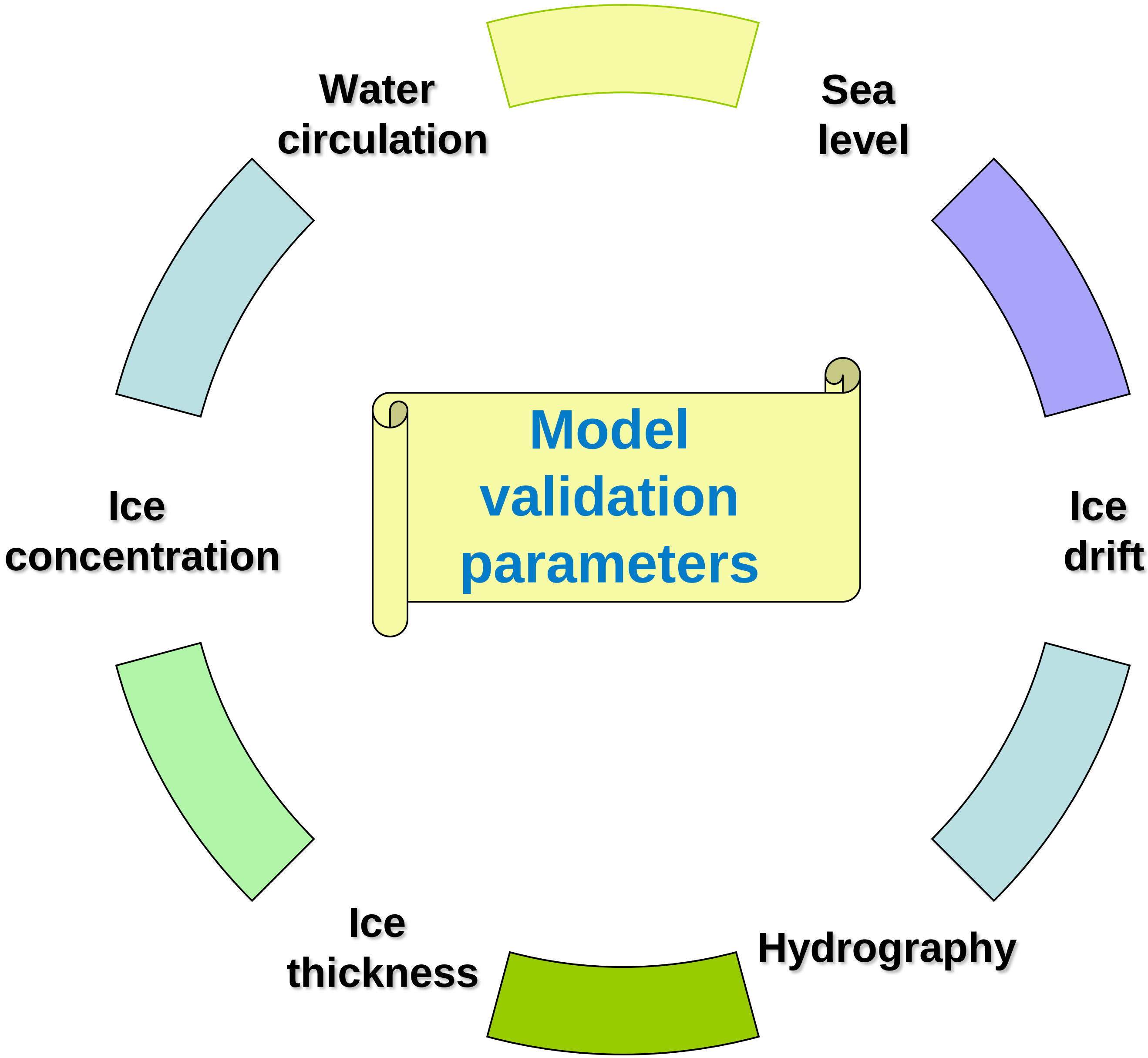
Ocean currents at 466 m with AOMIP forcing

Model validation

- The first group of studies has focused on the analysis of differences among model results and between model results and observations.

- This was a first step needed for a process of model improvements.

Model validation parameters



Data

Forcing Data Notation

Atmospheric Forcing Data

Hydrographic Forcing Data

Surface-Restoring Forcing Data

River-Runoff Forcing Data

Sea-Ice Forcing Data

Topographic Forcing Data

100-Year Run Atmospheric Forcing Data

Validation Data - WSC Moorings

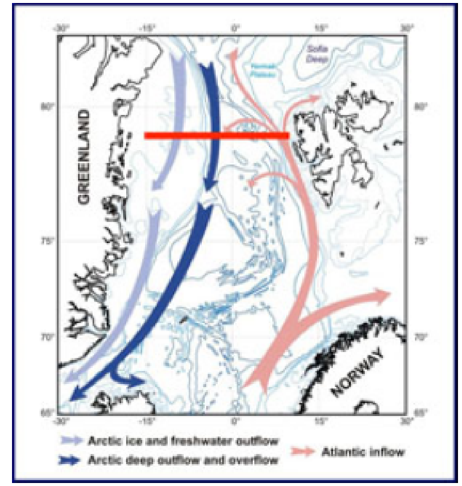
Validation Data - WSC Moorings

ShareThis Email Print PDF

A Fram Strait section, with a focus on the West Spitsbergen Current, has been covered with a varying number of moorings continuously since September 1997 in the framework of the EU projects VEINS (Variability of exchanges in the Northern Seas) and ASOF - N (Arctic Subarctic Ocean Fluxes - North):

- 1997 - 1999 : 14 moorings,
- 1999 - 2000 : 11 moorings,
- 2000 - 2002 : 14 moorings,
- 2002 - 2004 : ASOF - 17 moorings.

The water column was covered from 10 m above the seabed to about 50 m below the surface. The observations extend from the eastern Greenland shelf break (6°51'W) to the western shelf break of Spitsbergen (8°40'E) at the latitude 78°50'N (in 1997-2002 with a shift of the moorings west of 000°E to the latitude 79°N.

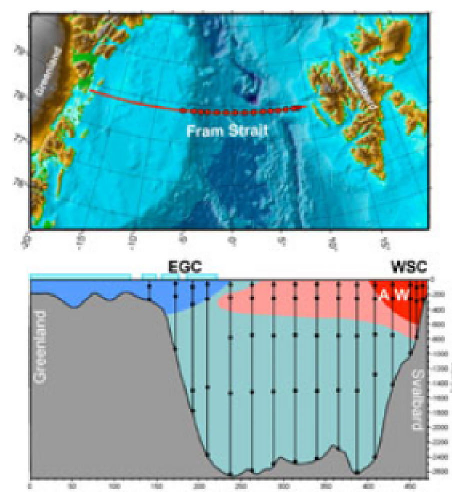


Enlarge Image

Fram Strait section.

A dataset is available comprised of monthly means of temperature and cross-section current (i.e., northward component) at 78°50'N :

1. averaged between 5°E and 8°40'E (the total width of the WSC included) within the Atlantic Water layer defined as:
   - layer 0-700 m (Mean_T_VC_5degE_700m.dat)
   - water with T > 1°C (Mean_T_VC_5degE_1degC.dat)
   - water with T >-0.1°C (Mean_T_VC_5degE_-0.1degC.dat)
2. averaged between 7°E and 8°40'E (the main core of the WSC included) within the Atlantic Water layer defined as:
   - layer 0-700 m (Mean_T_VC_7degE_700m.dat)
   - water with T >1°C (Mean_T_VC_7degE_1degC.dat)
   - water with T >-0.1°C (Mean_T_VC_7degE_-0.1degC.dat)



The data format is:

- Columns 1-3: year month day (day is not correct because data are centered in the

Currents and fluxes:

Model validation parameters

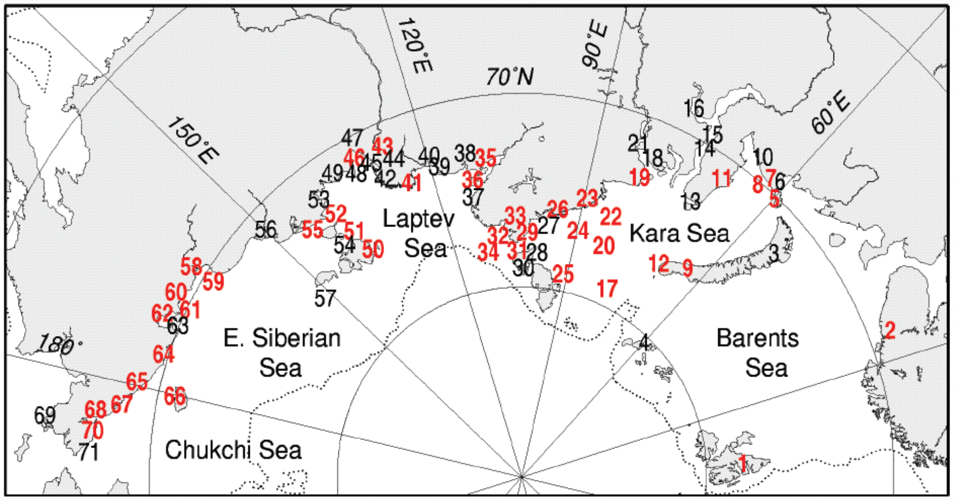
Tomorrow: **Model Skill Assessment (Dr. Greg Holloway, Fisheries and Oceans, Canada)**

Sea level

http://www.whoi.edu/science/PO/arcticsealevel/

Model validation parameters

Sea Level data sources



Sea level data sets were collected by the Arctic and Antarctic Research Institute for 71 stations (see station numbers) located in the Barents and Siberian Seas. time series of sea level variability generally cover the period between 1948 and 2000 but temporal coverage differs significantly from station to station. Red denotes stations with the most complete datasets.

INVESTIGATION OF ARCTIC SEA LEVEL RISE

Overview | Participants | Data | Publications | Presentations | Conclusions | Funding agencies

Overview

Recent outreach feedback
BBC news report - "Arctic dips as global waters rise"

Sea level is a natural integral indicator of climate variability. It reflects changes in practically all dynamic and thermodynamic processes of terrestrial, oceanic, atmospheric, and cryospheric origin. The use of estimates of sea level rise as an indicator of climate change therefore incurs the difficulty that the inferred sea level change is the net result of many individual effects of environmental forcing. Since some of these effects may offset others, the cause of the sea level response to climate change remains somewhat uncertain. This project is focused on an attempt to provide first order answers to two questions, namely:

1) What is the rate of sea level change in the Arctic Ocean? and
2) What is the role of each of the individual contributing factors to observed Arctic Ocean sea level change?

Unlike most other manifestations of climate change, sea level rise is already a significant problem throughout the Arctic (ARCUS, 1997; Shaw et al., 1998; Brown and Solomon, 2000; Forman and Johnson, 1998; IASC, LOIRA, 2000; Smith and Johnson, 2000). Global warming and the anticipated sea level rise in the Arctic is expected to influence shoreline erosion, sediment transport, navigation conditions, oil and gas operations, hunting, and other human activities. In January 2000, the Alaska Science and Technology Foundation sponsored a workshop entitled "The Warming World: Effects on the Alaska Infrastructure" (University of Alaska Anchorage). Workshop participants concluded that sea levels will rise, storms will be stronger and more

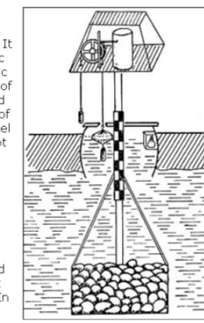
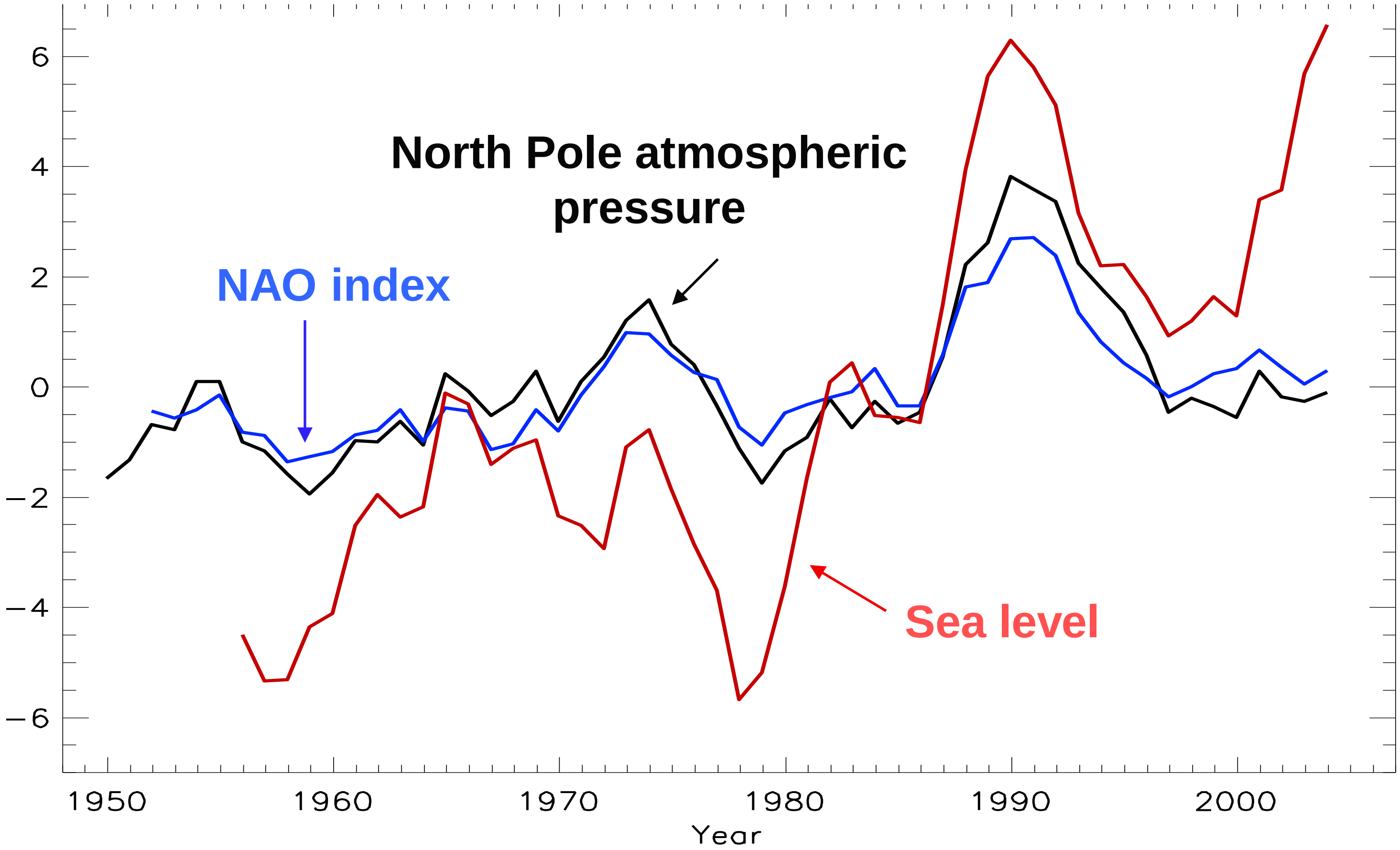


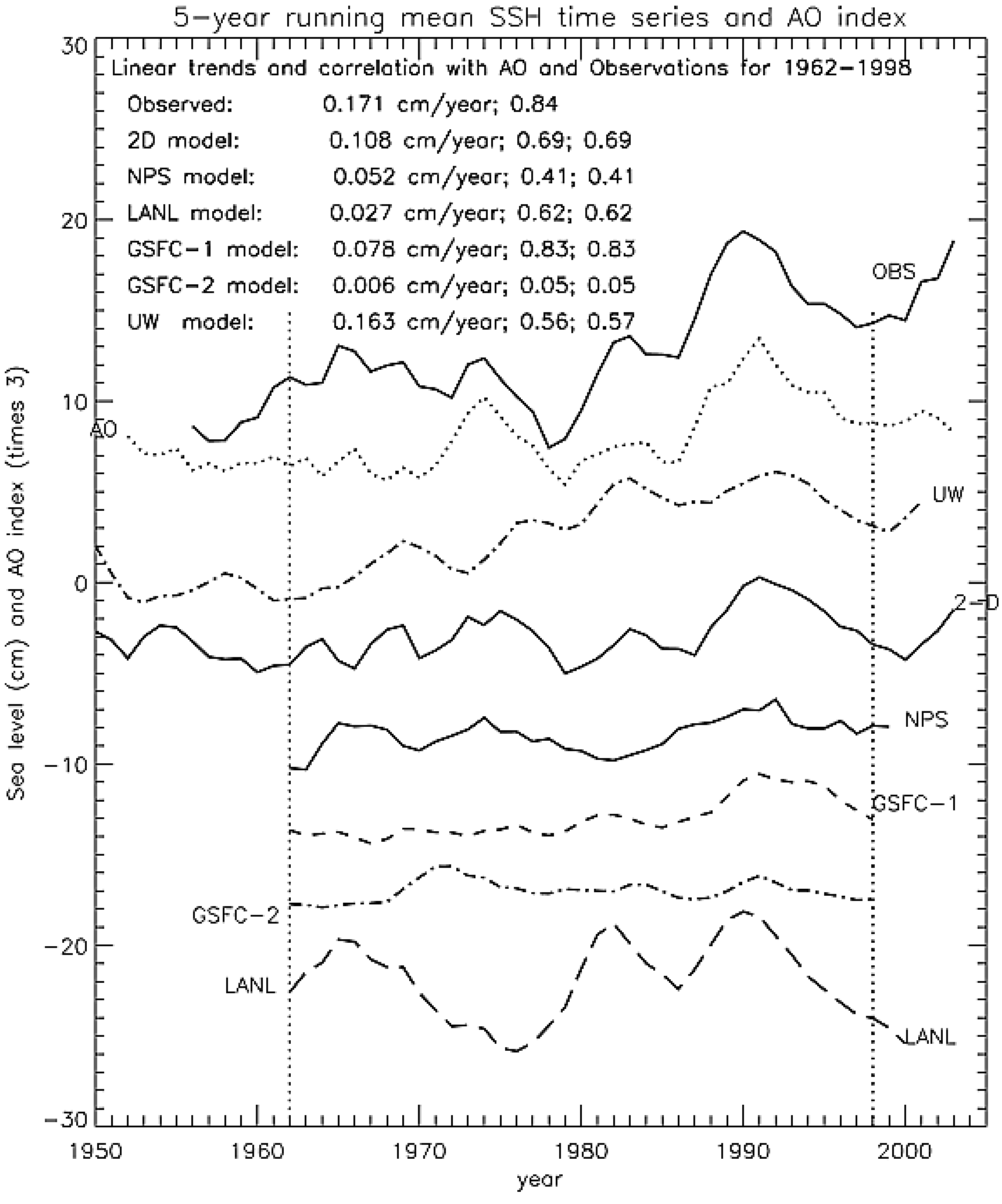
Diagram of a typical sea level gauge.

Sea level (cm)

Model validation parameters

Sea level variability correlates very well with the NAO index and with the atmospheric pressure at the North Pole. The sea level rise rate for 1950-present is approximately 10 cm per 50 years.





SSH 5-year running mean time series for all models. The data were averaged for 9 stations. Linear trends and correlation coefficients between simulated time series and AO and observed SL (OBS) are shown in left upper corner. Lines are shifted relative to 0 in order to better analyze differences. Note that LANL model time series was detrended to demonstrate decadal variability

Sea level validation results:

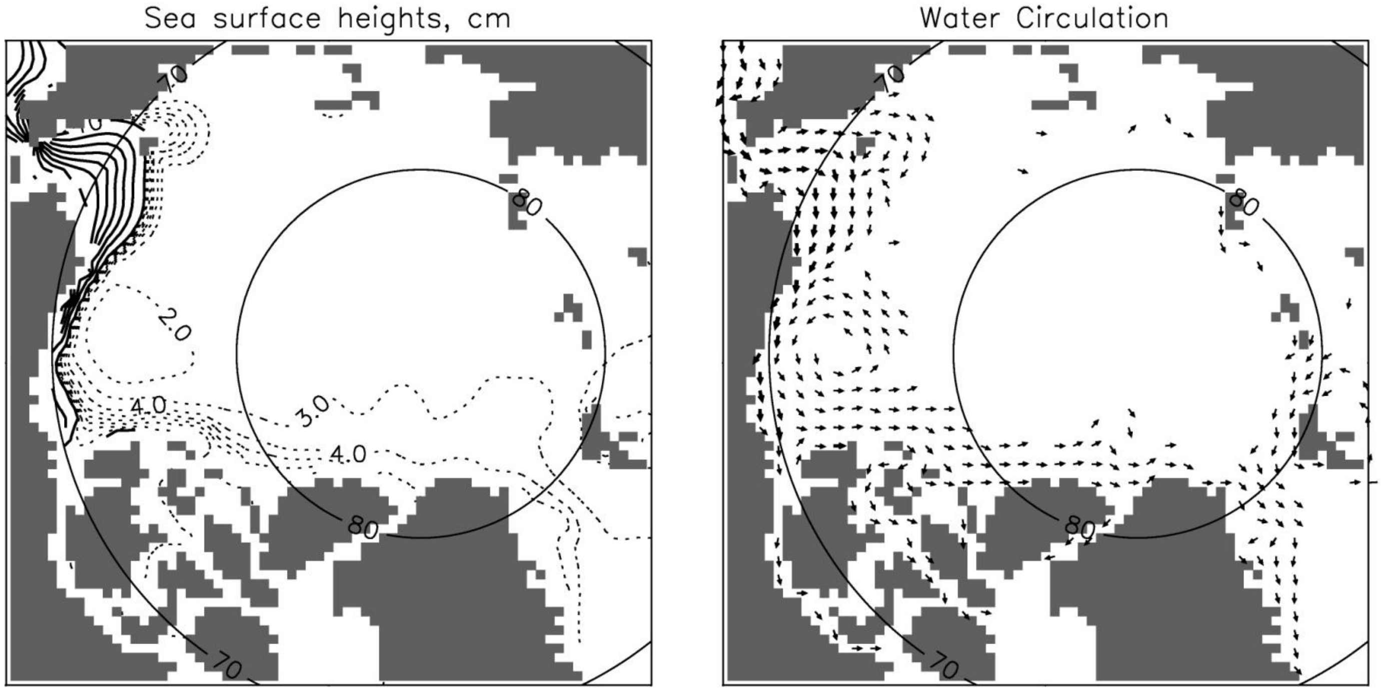
❖ In general, AOMIP ocean models with a free surface are able to simulate variability of SSH reasonably well but several improvements are needed to decrease model errors:

❖ It is found that in order to reproduce variability of SSH at the locations of tide gauges in the shallow Arctic seas, it is important to have a minimum depth of no more than 10 m.

❖ Models have to take into account forcing associated with atmospheric loading . This effect is responsible for SSH variability not only at synoptic timescales (for example, storms) but also changes at seasonal, interannual and long-term timescales.

❖ Inclusion of atmospheric loading in the oceanic model module must be accompanied by an atmospheric loading effect in the sea ice dynamics model module, to avoid artificial sea ice motion.

❖ Fast ice has to be taken into account as well. The implementation or parameterization of fast ice in 3-D models is an interesting and difficult task but it could be solved step by step, first implementing the relatively primitive empirical approach employed in our 2-D model simulations, then developing a model of fast ice formation and decay.



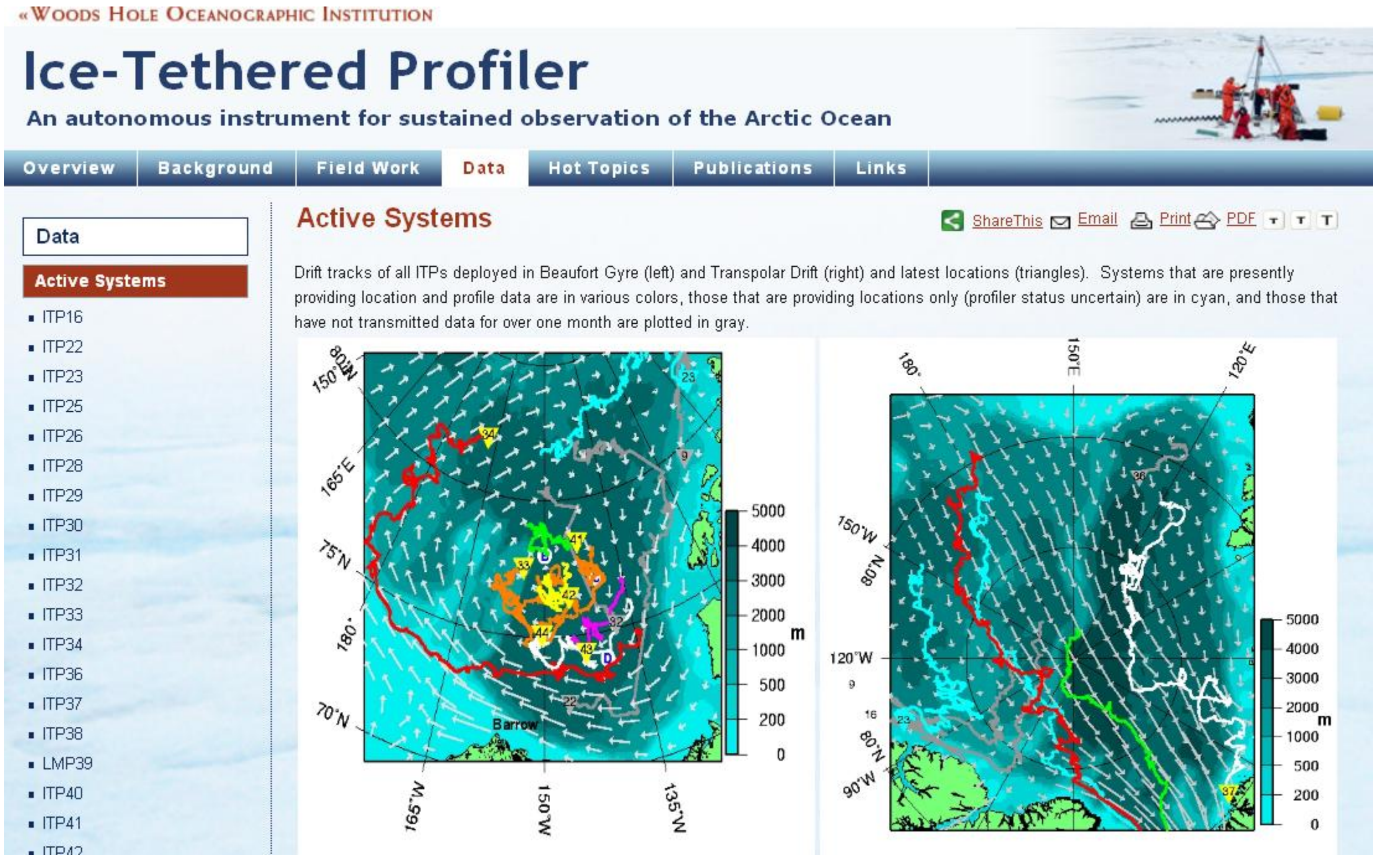
Sea surface (left) heights and (right) currents due to Bering Strait inflow.

The pressure gradient associated with the Bering Strait inflow should drive the entire circulation of the Beaufort Gyre from the surface to bottom layers cyclonically and can be responsible for one of the mechanisms influencing redistribution of the Pacific waters in the Canada Basin. Assuming that the surface layer of the Arctic Ocean in the Canada basin is driven by winds anticyclonically and that the depth of the Ekman layer is approximately 25–30 m, it can be concluded that below 40–50 m, the Pacific water circulates cyclonically and its circulation speed depends on the variability of the Bering Strait inflow. This inflow is also regulated by the wind regime over the Chukchi Sea and good correlation between wind forcing and circulation of Pacific waters is expected. It is also expected that in summer with diminishing anticyclonic winds, the cyclonic circulation of Pacific waters and all waters below the Ekman layer (including Atlantic and deep waters) intensifies.

Ocean T&S

There are numerous data sources especially after 2007-2009 IPY expeditions but unfortunately we do not have a new climatology of T&S for decade of 2000s (2000-2009).

Model validation parameters



On the other hand, since 2004 the Ice-tethered profiling data are available at: www.whoi.edu/itp in real time for both data assimilation and model validations

Water properties and circulation in Arctic Ocean models,

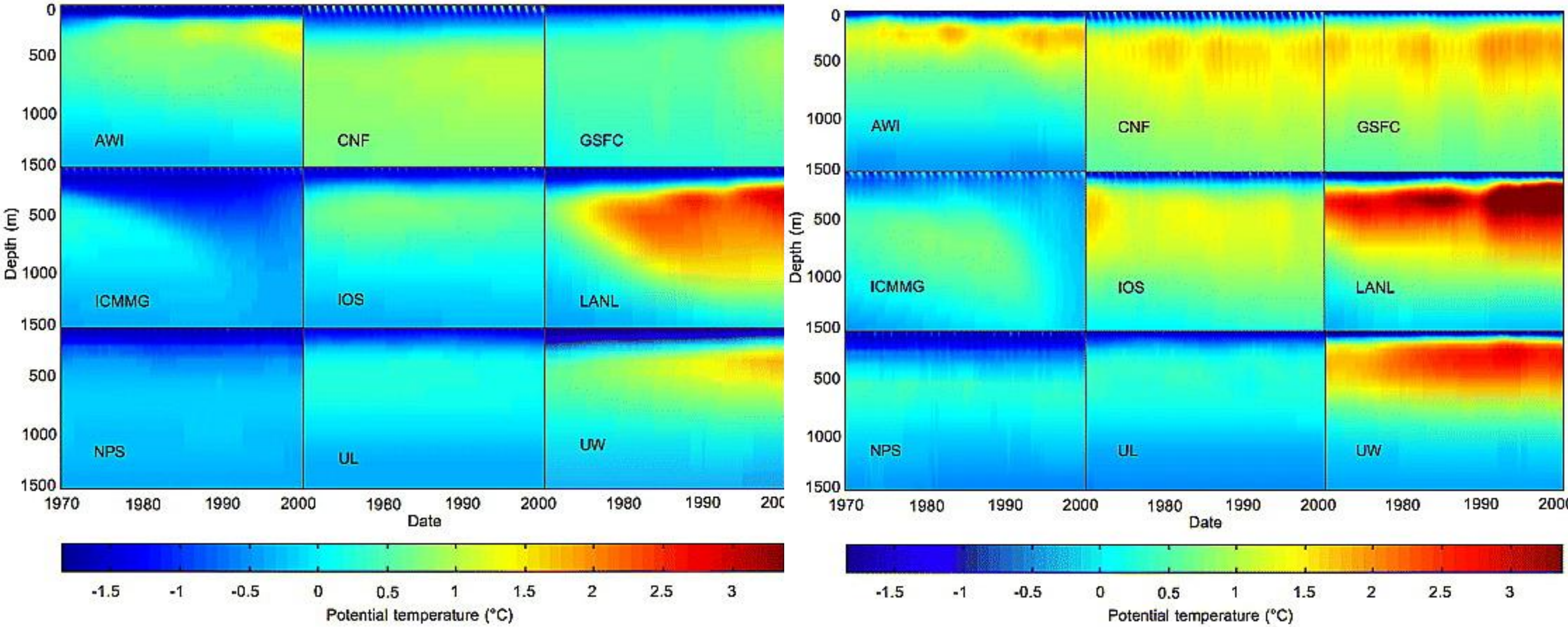
Holloway, G. et al., [2007]: JGR, J. Geophys. Res., 112, C04S03, doi:10.1029/2006JC003642

As a part of the Arctic Ocean Model Intercomparison Project, results from 10 Arctic ocean/ice models were intercompared over the period 1970 through 1999.

A first goal for AOMIP has been to identify key differences among Arctic models' outputs under conditions where initialization and forcing are as nearly common as possible.

Temperature intercomparison

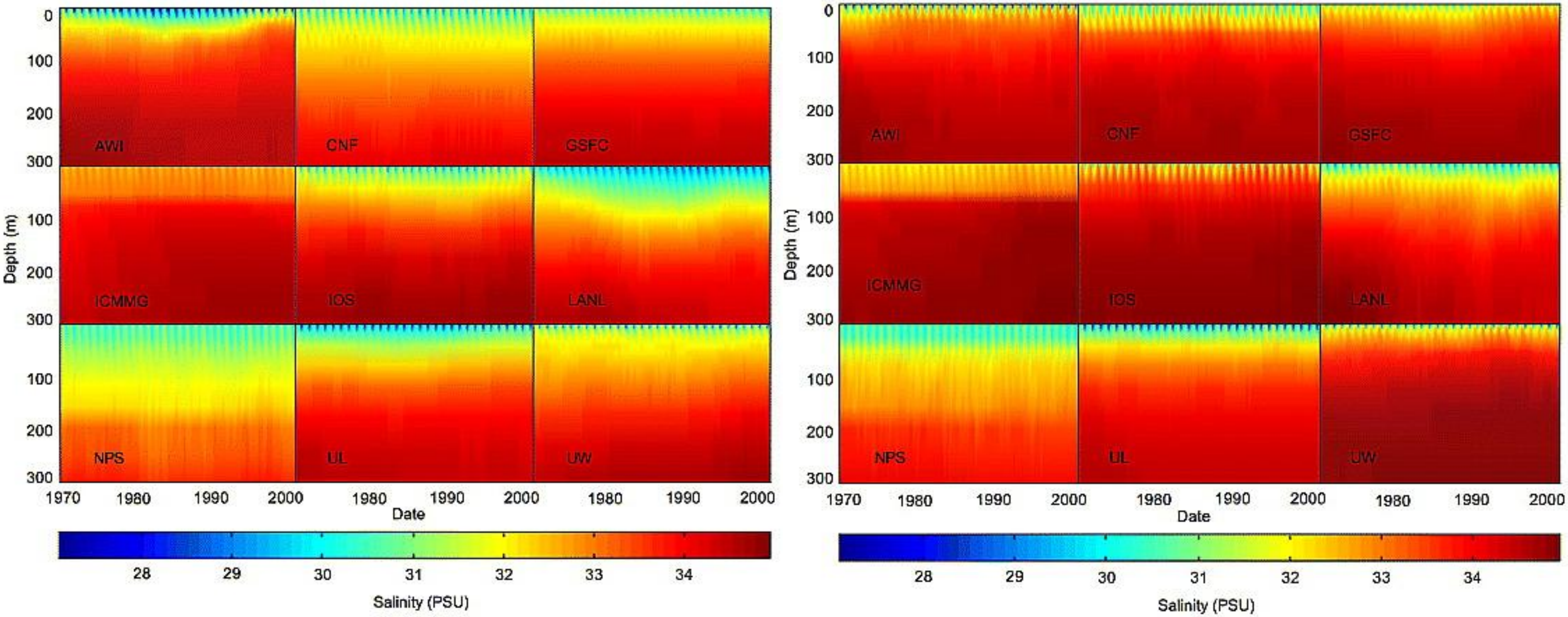
Amerasian Basin **Eurasian Basin**



Monthly mean potential temperature (°C) is shown as a function of depth and time for models AWI, CNF, GSFC, ICMMG, IOS, LANL, NPS, UL and UW

Salinity intercomparison

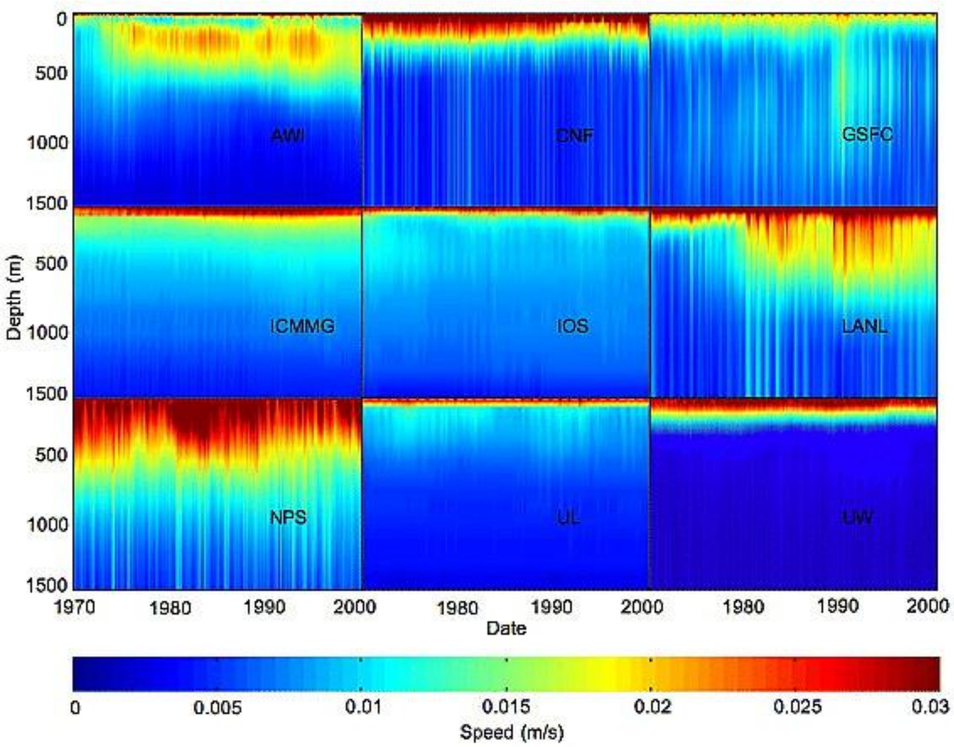
Amerasian Basin **Eurasian Basin**



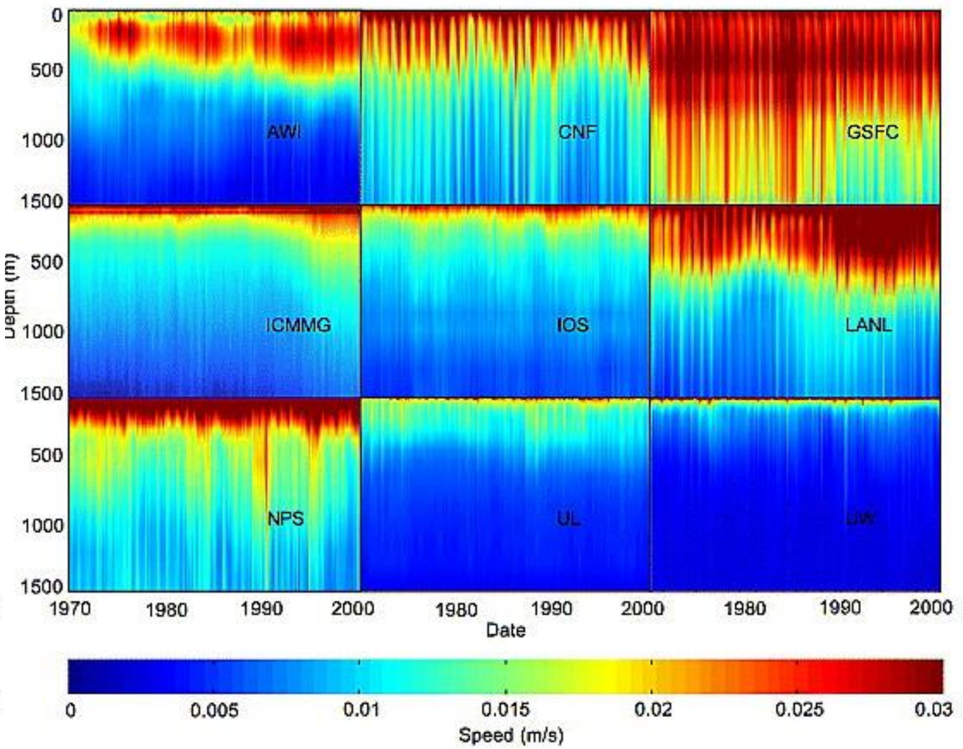
Monthly mean salinity is shown as a function of depth and time for models AWI, CNF, GSFC, ICMMG, IOS, LANL, NPS, UL and UW

Circulation intercomparison

Amerasian Basin



Eurasian Basin



Monthly current speed is shown as a function of depth and time for models AWI, CNF, GSFC, ICMMG, IOS, LANL, NPS, UL and UW

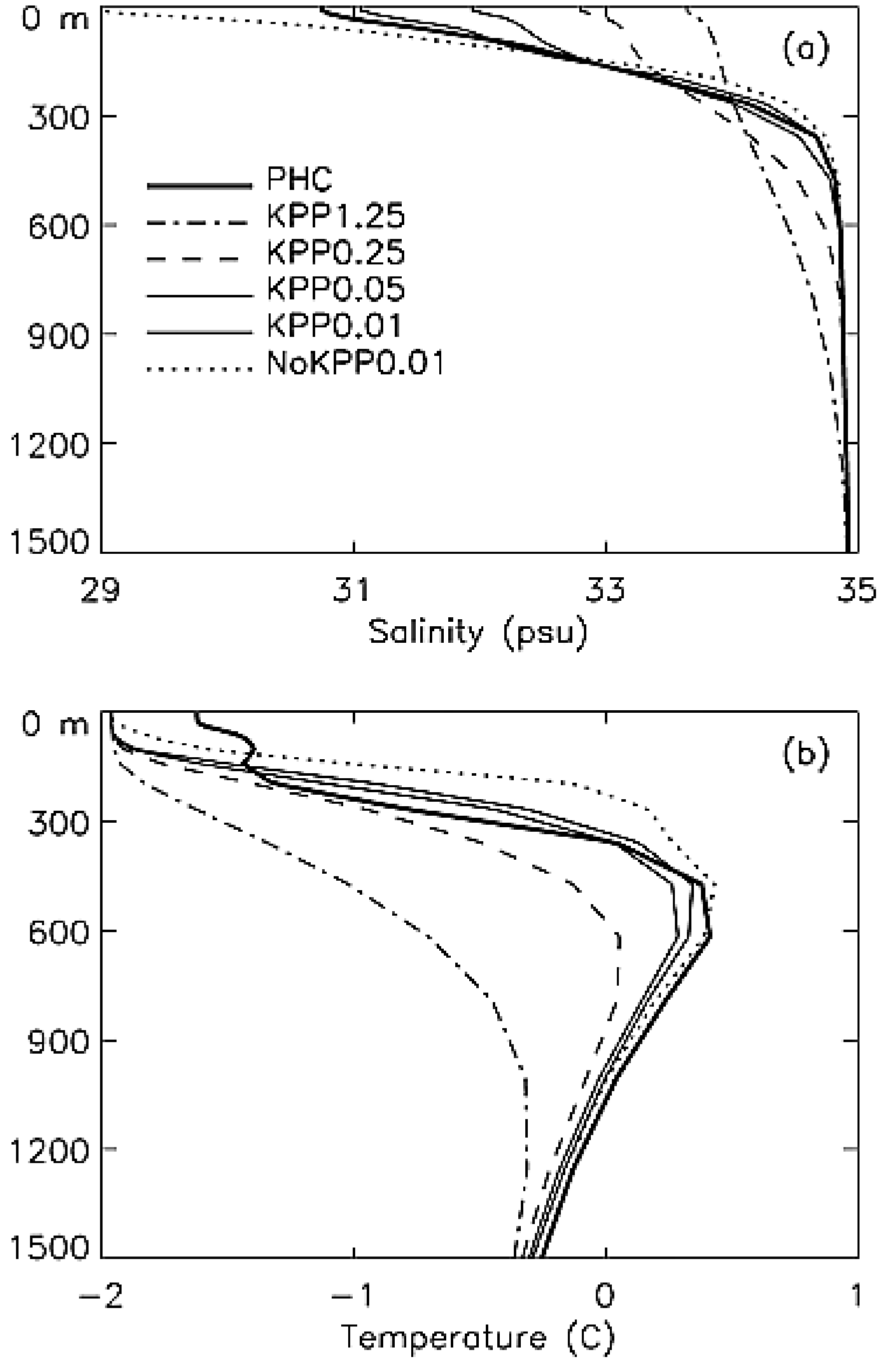
T&S and currents model intercomparison results:

In general: A systematic deficiency were seen as AOMIP models tend to produce thermally stratified upper layers rather than the "cold halocline", suggesting missing physics perhaps related to vertical mixing or to shelf-basin exchanges.

Systematic differences of models' circulations were found to depend strongly upon assumed roles of unresolved eddies.

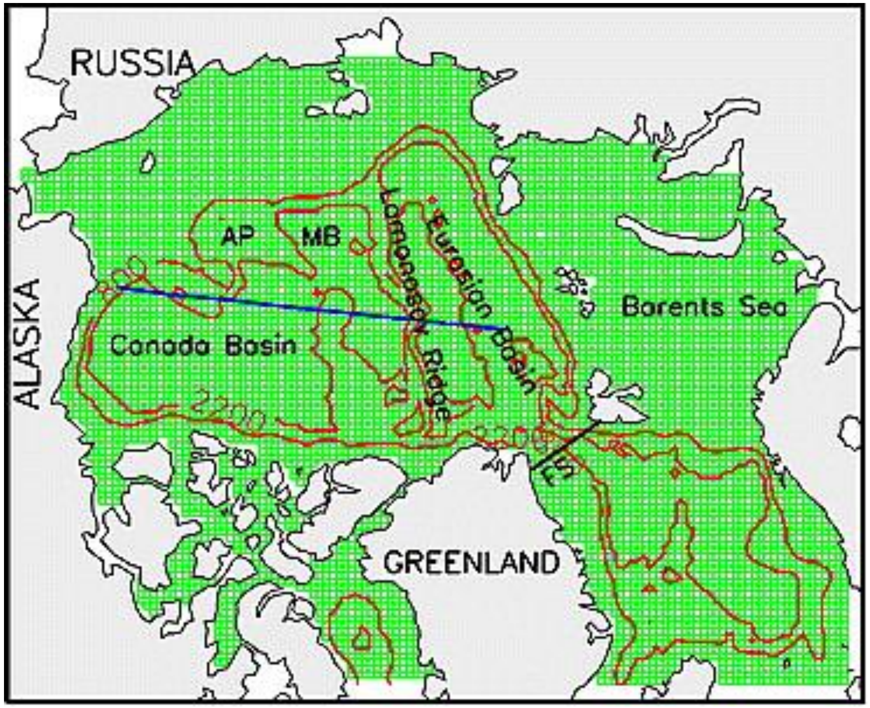
Important details: It is seen that the Atlantic Layer (defined by T > 0°C) tends to become too thick, extending too deep in comparison with EWG. This is depends upon the quality of numerical advection, which can require excessive diffusion to prevent spurious dispersion. Advanced numerical methods, e.g., second order moment advection [Prather, 1986], can limit over-deepening. It is further seen that the suite of AOMIP models tend to show systematic growth of ocean heat over the entire AOMIP period 1950 to 2000, contrary to decadal averages from EWG over 1950 to 1990.

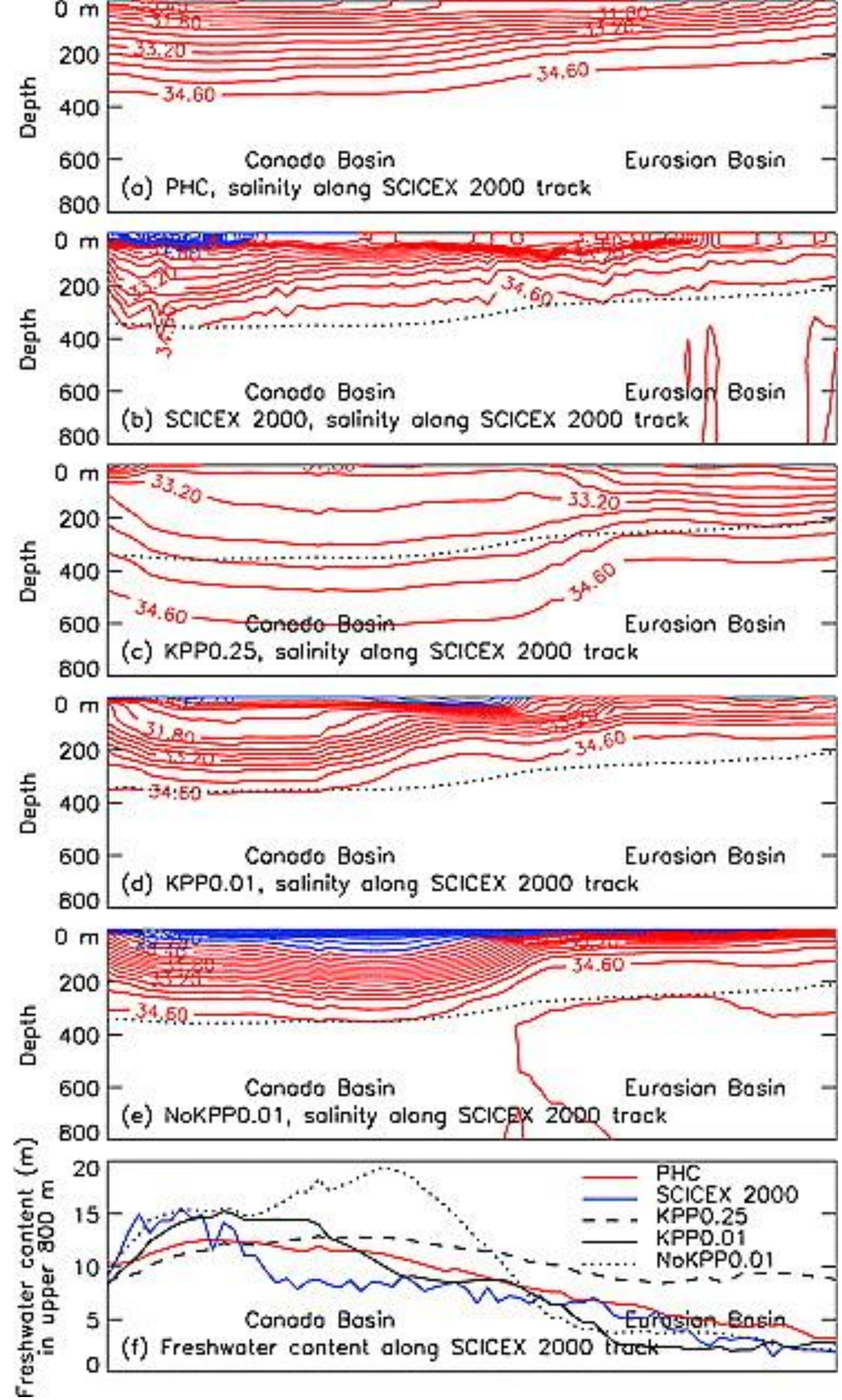
The failure to form the "cold halocline" is not explained and suggests missing or misrepresented physics across the suite of AOMIP modeling.



Zhang, J., and M. Steele (2007), Effect of vertical mixing on the Atlantic Water layer circulation in the Arctic Ocean, *J. Geophys. Res.*, 112, C04S04, doi:10.1029/2006JC003732.

The effect of vertical mixing on ocean stratification was investigated with varying degrees of vertical mixing parameterized K-profile parameterization (KPP) scheme [Large et al., 1994]. Mixing below the surface mixed layer is strongly influenced by a “background” diffusivity which were varied from a high value of 1.25 $cm^2 s^{-1}$ (KPP1.25), a medium-high value of 0.25 $cm^2 s^{-1}$ (KPP0.25), a medium-low value of 0.05 $cm^2 s^{-1}$ (KPP0.05) and a low value of 0.01 $cm^2 s^{-1}$ (KPP0.01).





The 1978 mean vertical distribution of salinity (a–e) and freshwater (FW) content integrated in the upper 800 m (f) along the cruise track of SCICEX 2000. Reference salinity of 34.8 psu is used to calculate the FW content. Blue (red) contours in (b–e) represent salinity below (above) 30.00 psu with contour interval 0.35 psu. The dotted line in (b–e) is the 34.60 psu contour from (a).

More T&S and currents model intercomparison results:

It was found that varying vertical mixing significantly changes the ocean's stratification by altering the vertical distribution of salinity and hence the structure of the arctic halocline.

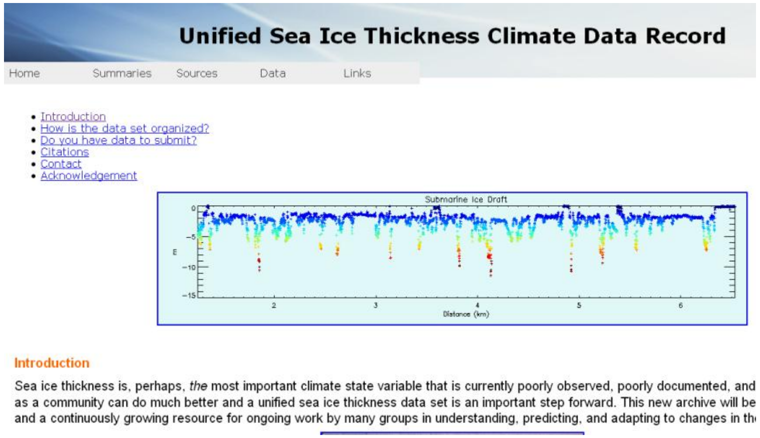
Excessively strong vertical mixing drastically weakens the ocean stratification, leading to an anticyclonic circulation at all depths.

Overly weak vertical mixing makes the ocean unrealistically stratified, with a fresher and thinner upper layer than observations. This leads to an overly strong anticyclonic circulation in the upper layer and an overly shallow depth at which the underlying cyclonic circulation occurs.

By allowing intermediate vertical mixing, the model does not significantly drift away from reality and is in a rather good agreement with observations of the vertical distribution of salinity throughout the Arctic Ocean.

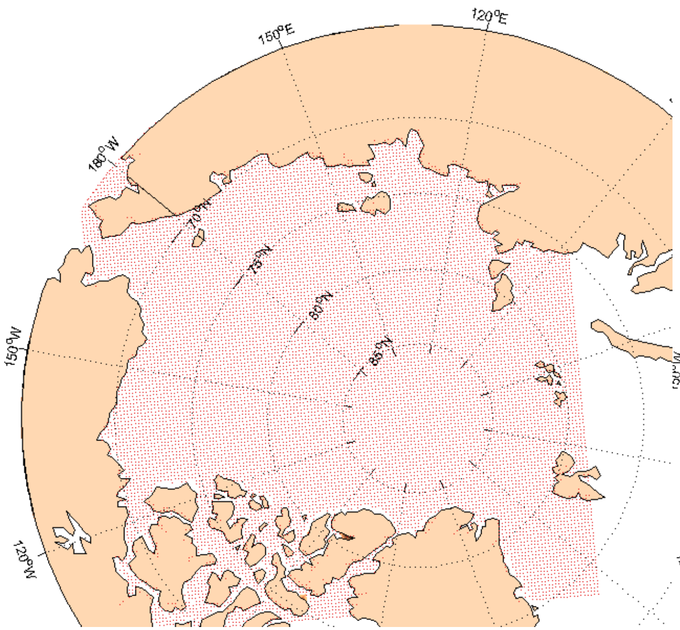
Sea ice: concentration, thickness, drift and deformations

Model validation parameters

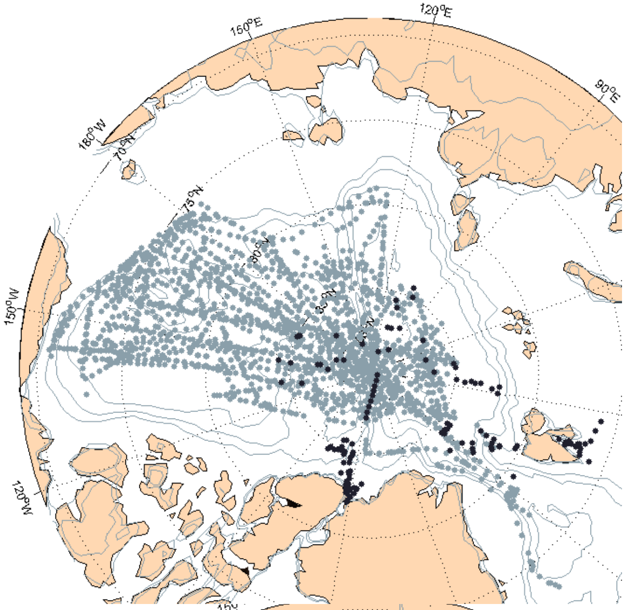


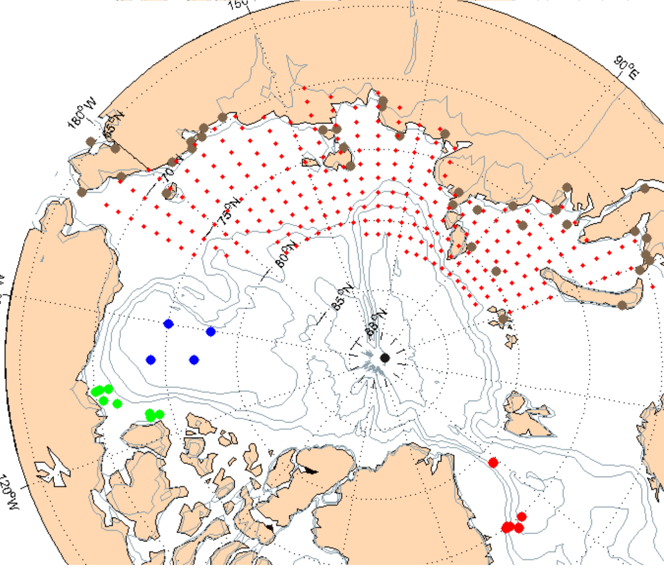
Most of the used data sets are archived at the National Snow and Ice Data Center (NSIDC). Also see R. Lindsay's web site at http://psc.apl.washington.edu/sea_ice_cdr/

ICESat Data



Submarine and Airborne EM Stations

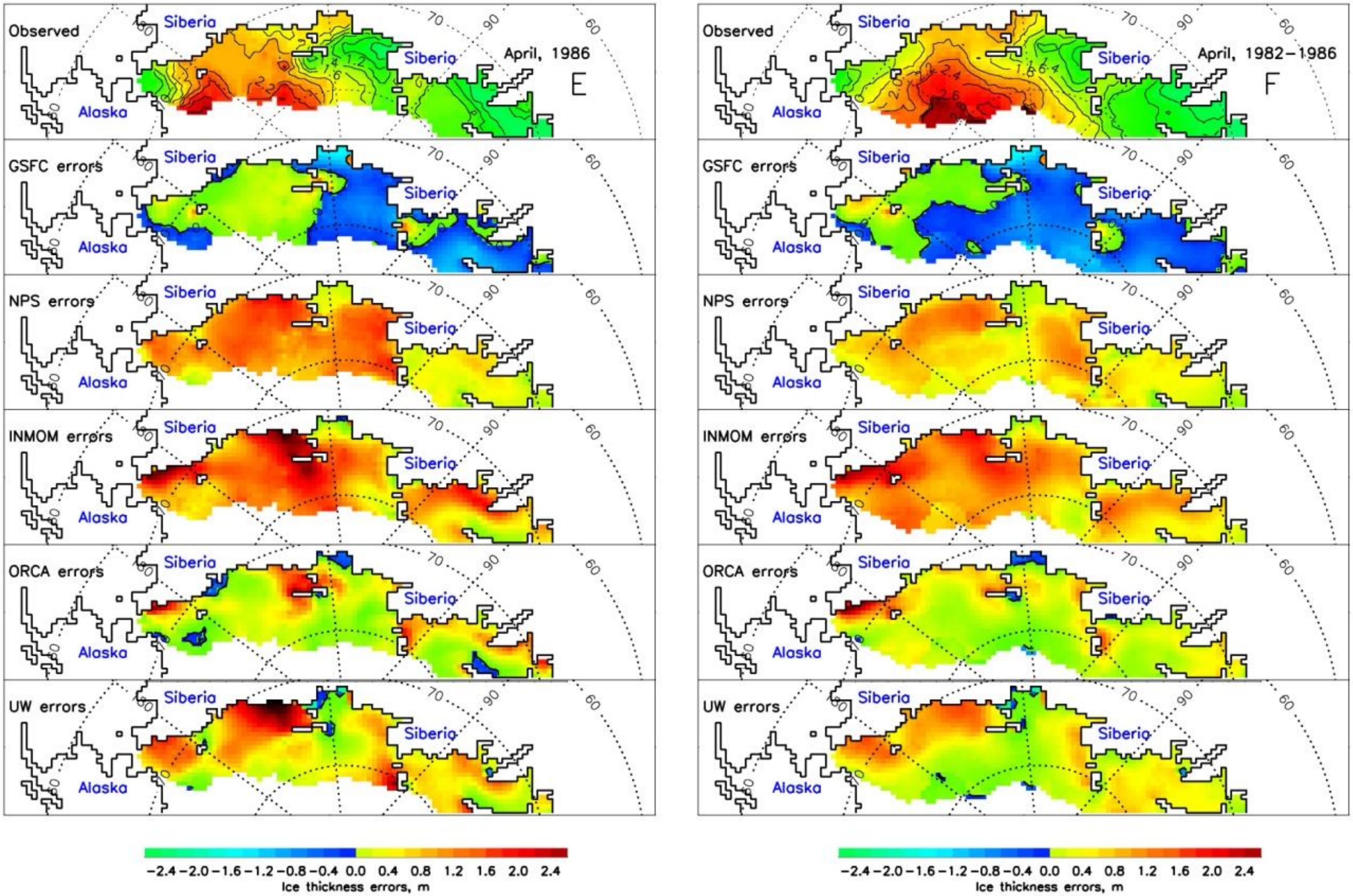




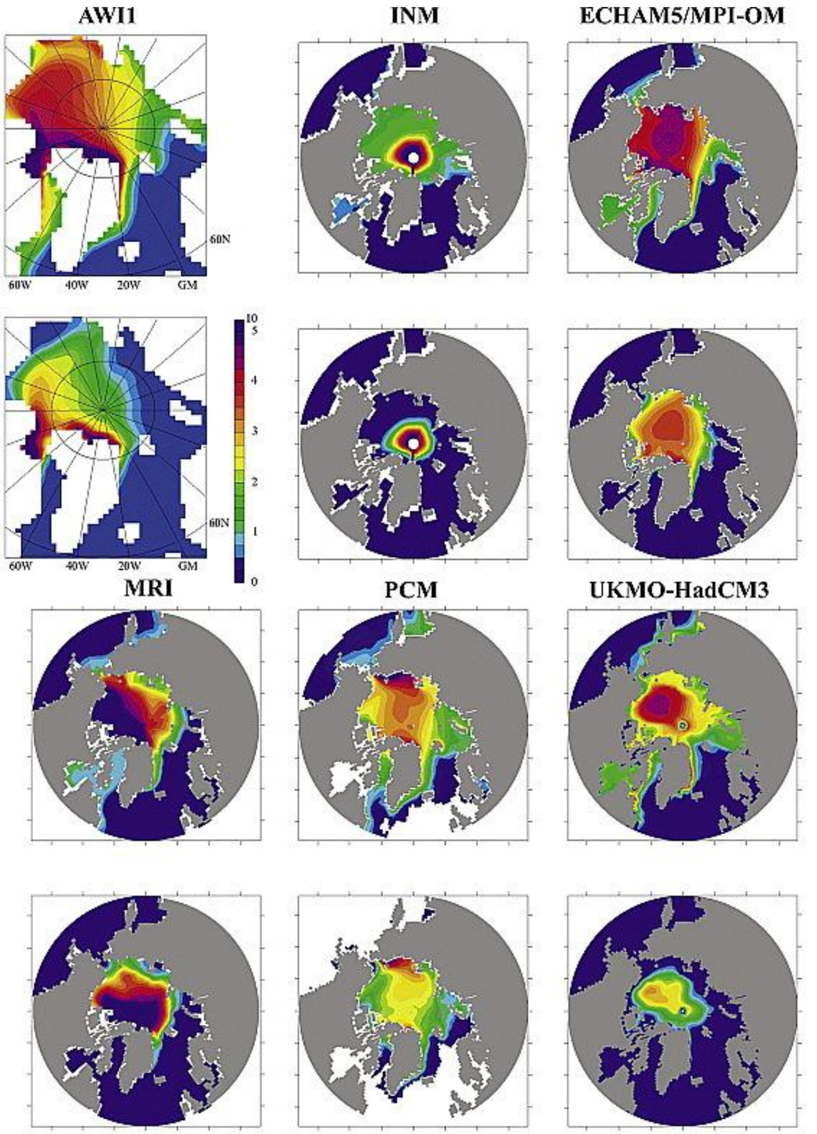
Sea ice thickness model validation conclusions

- Recently, the results from six AOMIP model simulations were compared with estimates sea ice thickness obtained from ICESat, moored and submarine-based upward looking sensors, airborne electromagnetic measurements and drill holes through ice (Johnson et al., 2011). While there are important caveats when comparing modeled results with measurements from different platforms, the best agreement was reported between the satellite data and the models. In general, most of the AOMIP models underestimate thicker sea ice (>2 m) and overestimate thinner ice (< 2 m). The simulated results are poorest over the fast ice region of the Siberian shelves.

- Comparison of model thickness with fastice thickness (including overlying snow) from drill holes along the Siberian shelf show that most models overestimate thickness. The largest offsets from the observations are in the Siberian Sea shelf where GSFC underestimates the thickness by as much as 2.5m and INMOM overestimates thickness by the same amount.


Observed
April, 1986
E
Observed
April, 1982–1986
F
GSFC errors
NPS errors
INMOM errors
ORCA errors
UW errors
Siberia
Alaska
−2.4 −2.0 −1.6 −1.2 −0.8 −0.4 0.0 0.4 0.8 1.2 1.6 2.0 2.4
Ice thickness errors, m

Sea ice thickness



- Because of lack of ice thickness observational data, for an assessment of coupled climate models their behavior is compared with results from an ocean–sea ice model using the Arctic Ocean Model Intercomparison Project (AOMIP) atmospheric forcing for the period 1948–2000 and the AOMIP model result is used as a benchmark for the coupled climate models.

Mean (1950–2000) April (upper panels) and September (lower panels) ice thickness distribution for the AWI1 AOMIP hindcast simulation (upper row, left) and selected IPCC model results.

Sea ice thickness model validation conclusions

- There are considerable errors in sea ice thickness in IPCC results. (too simple sea ice rheologies in some of these models. Better models tend to pile up ice in the center of the ocean).

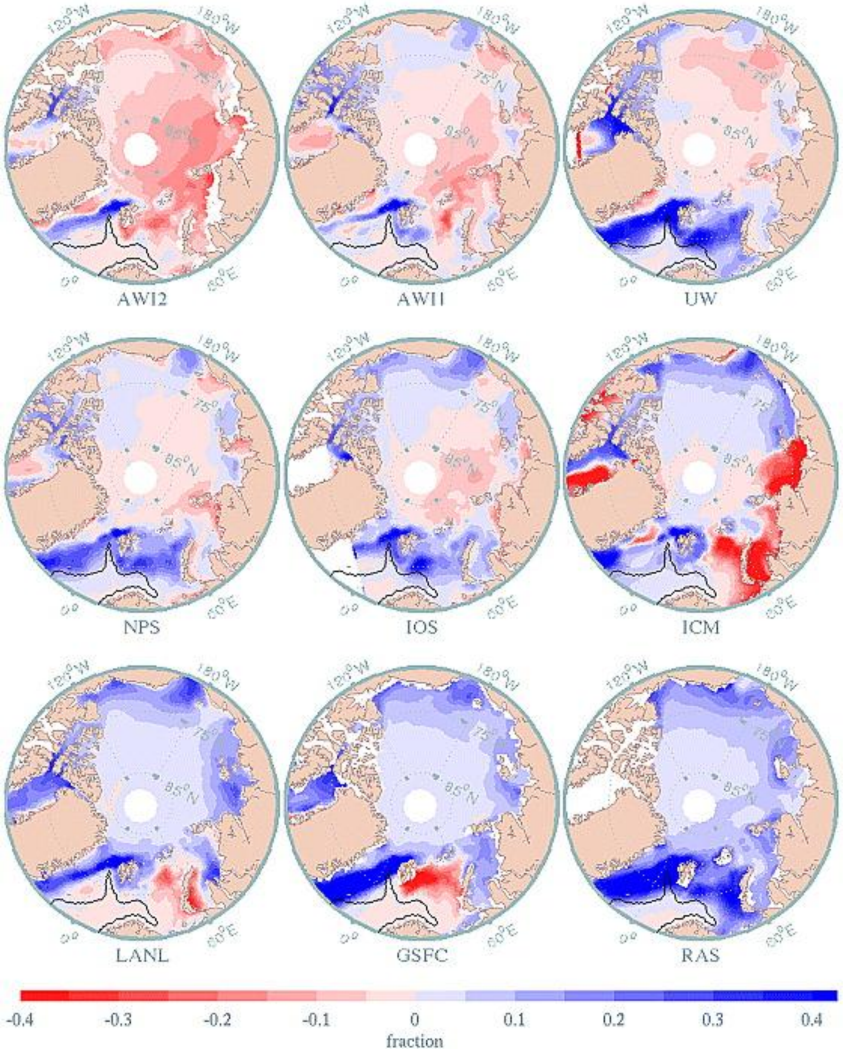
- Errors may have important consequences for the atmospheric circulation. Too large ice cover and thickness in the European sector could be significant in ocean-atmosphere interactions and long term variability.

- The AOMIP results are dominated by an accumulation of sea ice in the mid-1960s and a return to values before that event in the last decade of the 20th century.

- The IPCC results show a negative trend in Arctic sea ice volume over the 20th century. The AOMIP simulation shows no trend over that period. This suggests that the internal multidecadal variability of the real climate system is underestimated in IPCC models.

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

Sea ice concentration



Differences for each model between the mean model sea ice concentration and the mean sea ice from GSFC for 1979–1999. The dark line is the 0.001 concentration contour from the GSFC data. Models from left to right and top to bottom are AWI2, AWI1, UW, NPS, IOS, ICM, LANL, GSFC, and RAS. Scale is from −0.4 (red) to +0.4 (blue) with values nearer zero having less color saturation. Saturated colors indicate larger differences from the observations with red below and blue above the observed.

Sea ice concentration model validation conclusions

- **Differences among the sea ice concentrations computed by the AOMIP models are greater than differences among four observational data sets.**

- **Regardless of the different model physics and parameters, the results show that the models have more variability than observed, and that, compared to observations, almost all the models underestimate the September sea ice concentration in the central Arctic Ocean.**

- **This underestimation may have important implications for sea ice forecasts.**

Sea ice: concentration, thickness, drift and deformations

Model validation parameters

Jet Propulsion Laboratory
California Institute of Technology

JPL HOME | EARTH | SOLAR SYSTEM | STARS & GALAXIES | SCIENCE & TECHNOLOGY

BRING THE UNIVERSE TO YOU: JPL Email News | RSS | Podcast | Video

MEaSUREs: Small-Scale Kinematics of Arctic Ocean Sea Ice

HOME
PROJECTS
PUBLICATIONS
CV
CONTACT

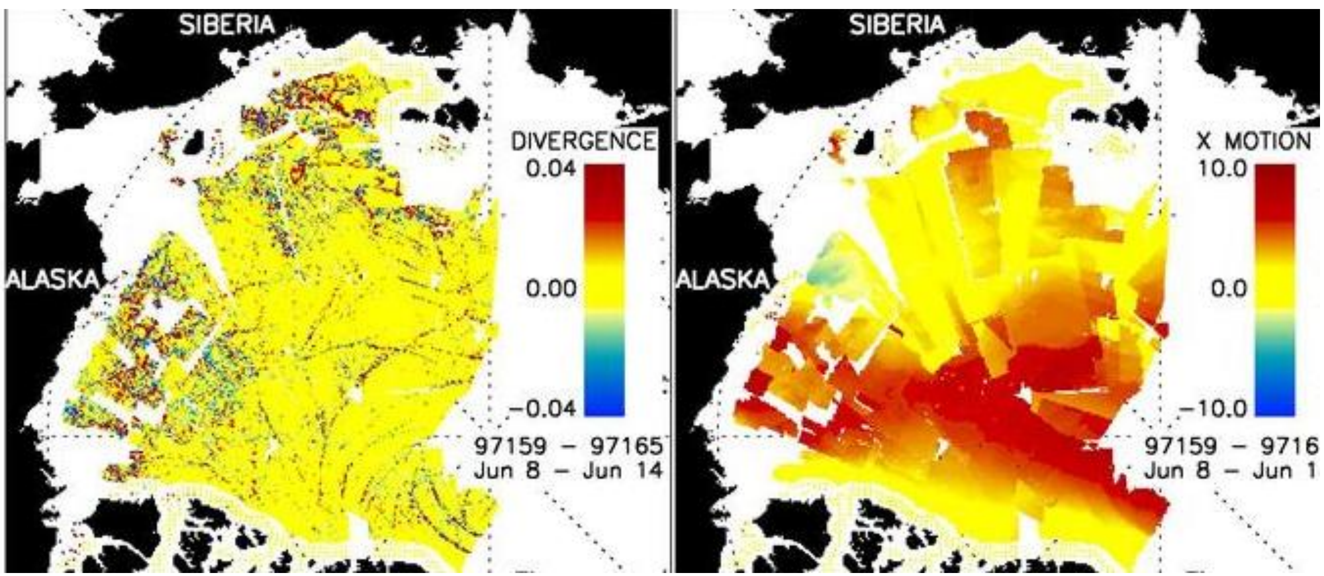
Overview | Data | Graphics

> Home > RADARSAT

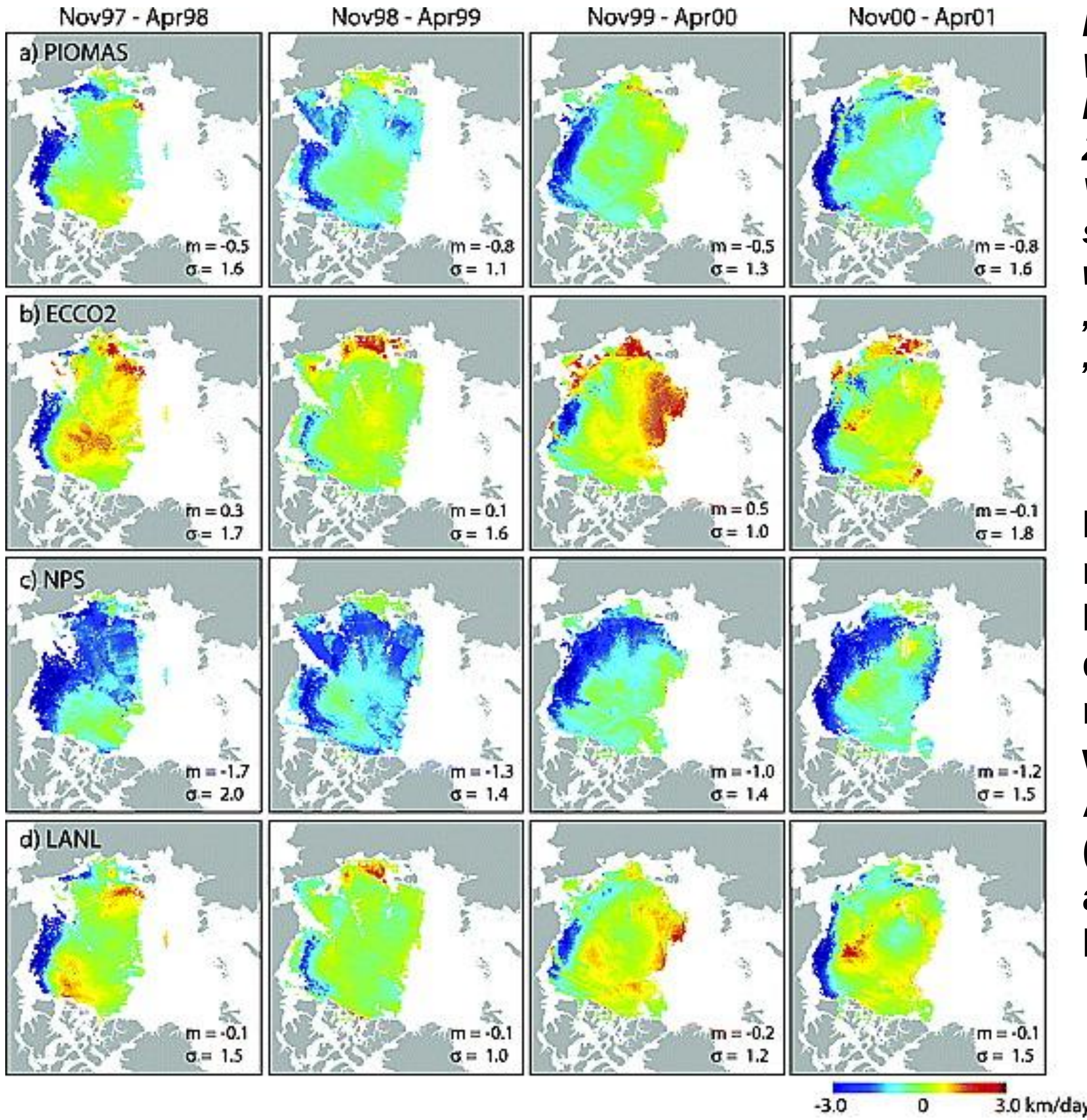
RADARSAT-1 has provided over eleven years of near-uninterrupted 3-day snapshots of the Arctic Ocean ice cover. In this project the SAR imagery from RADARSAT-1 is used to track the sea ice on a high-resolution grid to produce a data set of small-scale kinematics and deformation. This data set has contributed significantly to sea ice science in: the development of new approaches for modeling the mechanical behavior of sea ice and the validation of these models; the characterization of the sub-daily ice motion; a description of the seasonal and regional variability of sea ice deformation; the validation of ICESat freeboard algorithms; and, the estimates of sea ice exchange between the Arctic Ocean and the peripheral seas.

We are processing the data stream:
1) to construct a near decadal record of small-scale ice motion of the Arctic Ocean
2) to produce a record of ice motion of the northern Bering Sea
3) to assemble bi-weekly high-resolution image mosaics of the Arctic Ocean

The sequential radar observations, from RADARSAT, are transformed into estimates of ice motion, deformation, age and thickness by the RADARSAT Geophysical Processor System (RGPS).

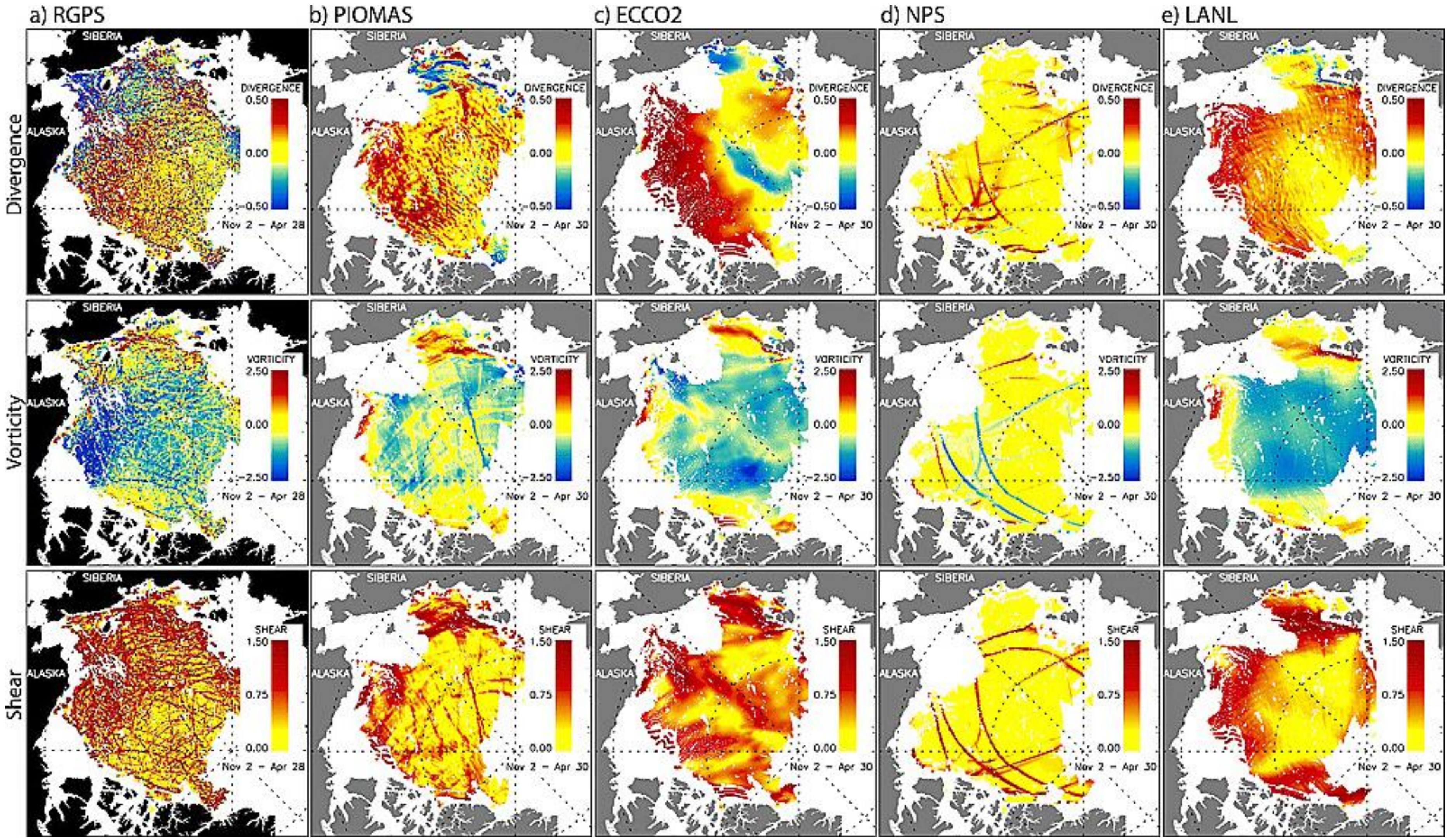


See Ron Kwok results at: http://rkwok.jpl.nasa.gov/index.html



Kwok, R., E. C. Hunke, W. Maslowski, D. Menemenlis, and J. Zhang (2008), Variability of sea ice simulations assessed with RGPS kinematics , J. Geophys. Res. , 113 , C11012.

Differences between monthly model and RGPS displacements magnitudes for four winters (November–April). (a) PIOMAS, (b) ECCO2, (c) NPS, and (d) LANL (units: km d^{-1})



Contrast between the net winter deformation (divergence, vorticity, and shear) from model simulations and RGPS ice drift. (a) NPS, (b) PIOMAS, (c) ECCO2, (d) NPS, and (e) LANL (strain rate units: d^{-1}).

RGPS model validation results:

Sea ice drift and deformation from coupled ice-ocean models were compared with high-resolution ice motion from the RADARSAT Geophysical Processor System (RGPS). Model fields were examined in terms of ice drift, export, deformation, deformation-related ice production, and spatial deformation patterns.

Even though the models are capable of reproducing large-scale drift patterns, variability among model behavior is high.

When compared to the RGPS kinematics, the characteristics shared by the models are:

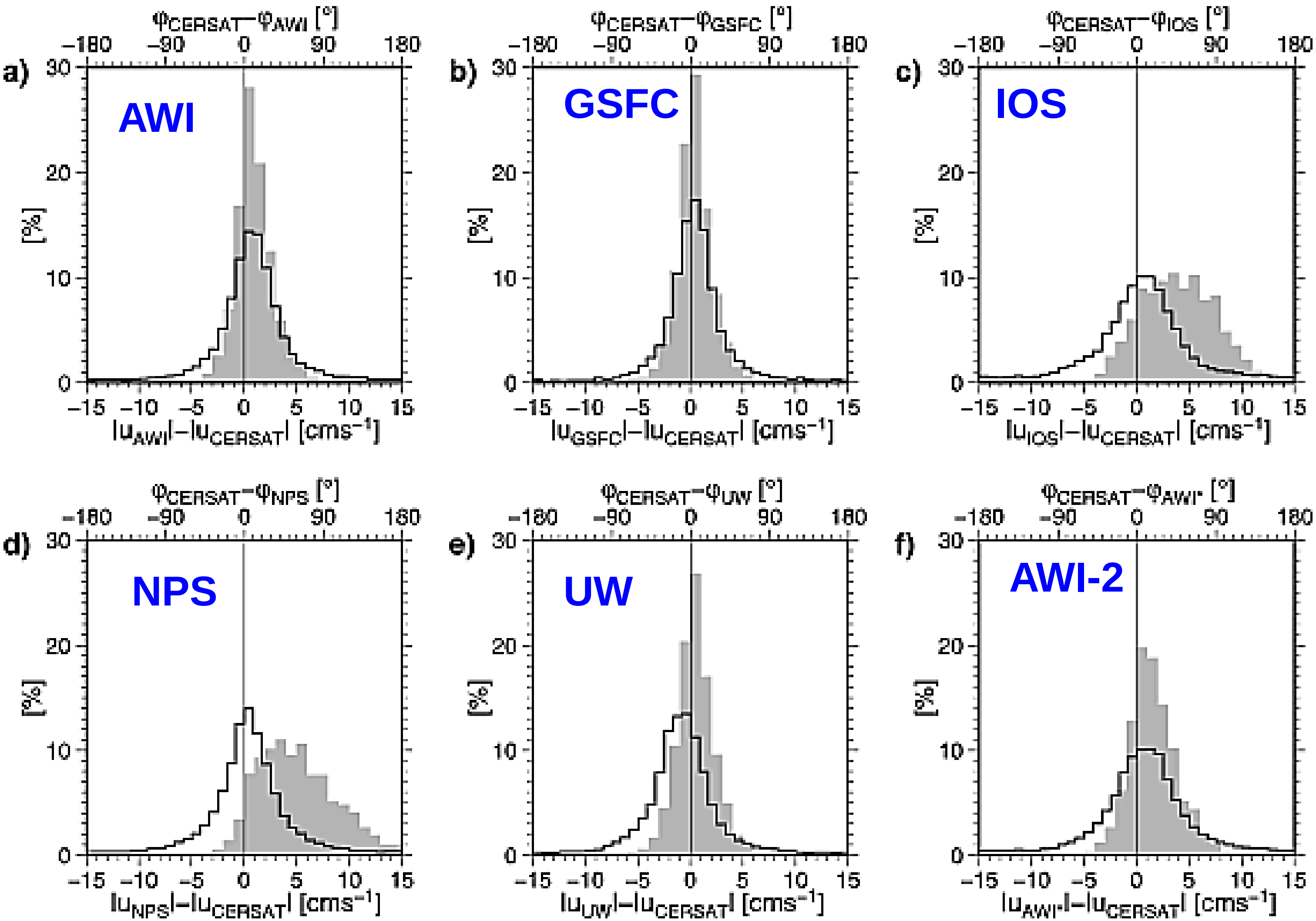
- **ice drift along coastal Alaska and Siberia is slower,**

- **the skill in explaining the time series of regional divergence of the ice cover is poor, and**

- **the deformation-related volume production is consistently lower.**

Sea ice drift

- Gridded observational ice drift fields were used from two products: NSIDC (Fowler, 2003); CERSAT (Ezraty, and Piollé, 2004)



Difference between model CERSAT ice drift speeds (gray shade) and direction (black outline).

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Sea ice drift model validation results

- **One class of models has a mode at drift speeds around 3 cm/s and a short tail toward higher speeds. Another class shows a more even frequency distribution with large probability of drift speeds of 10 to 20 cm/s. Observations clearly agree better with the first class of model results.**
- **Reasons for these differences lie in discrepancies in sea ice model characteristics and sea ice-ocean coupling.**
- **In general, the models are capable of producing realistic drift pattern variability.**

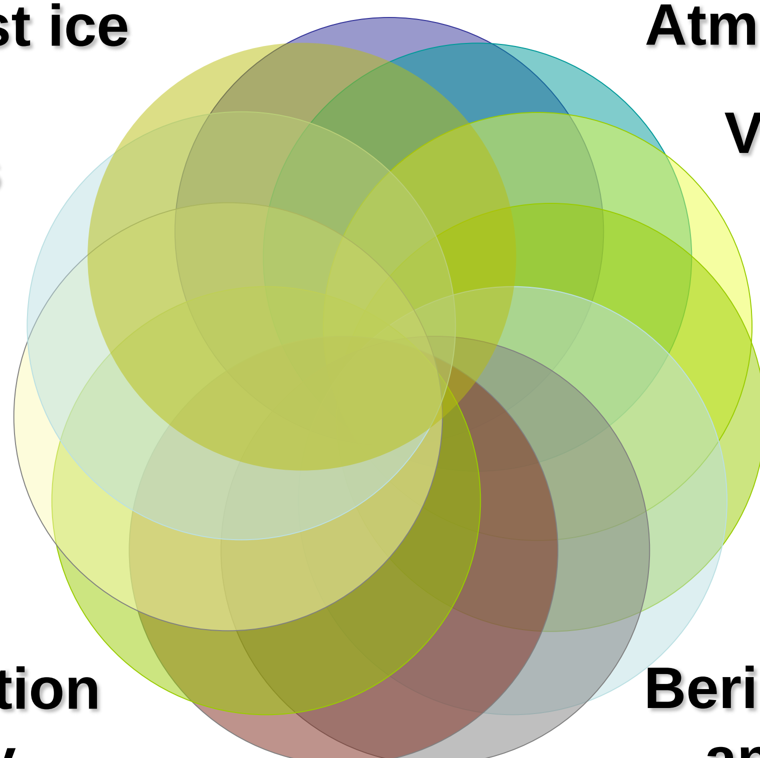
Model improvements

AOMIP model improvement has included several phases:

- ❑ **- Identification of problems;**
- ❑ **- Search for solutions/improvements;**
- ❑ **- Testing improvements based on one or two models;**
- ❑ **- Recommendations to others; and**
- ❑ **- Introduction and testing of new ideas.**

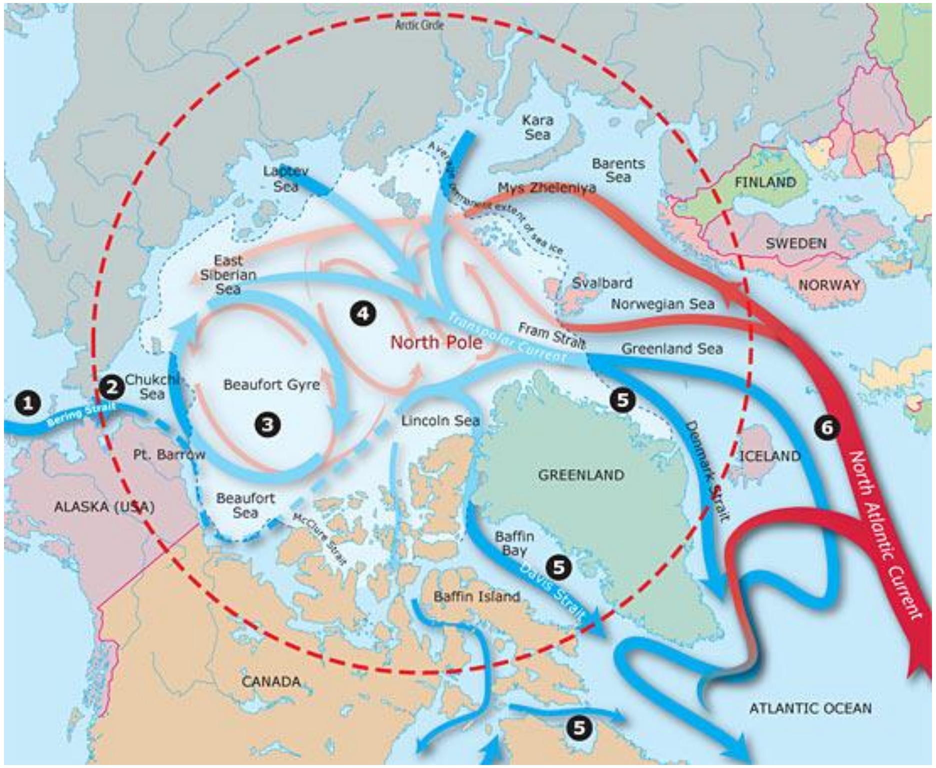
Following this scheme, several mechanisms and parameterizations have been applied and analyzed.

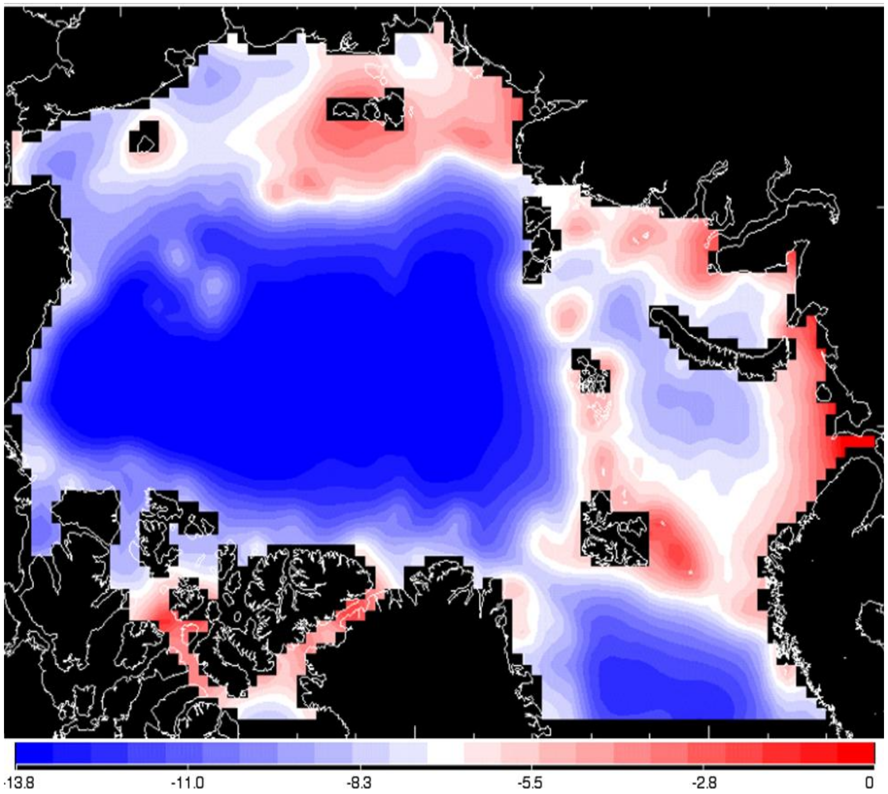
Model improvements



Model improvement

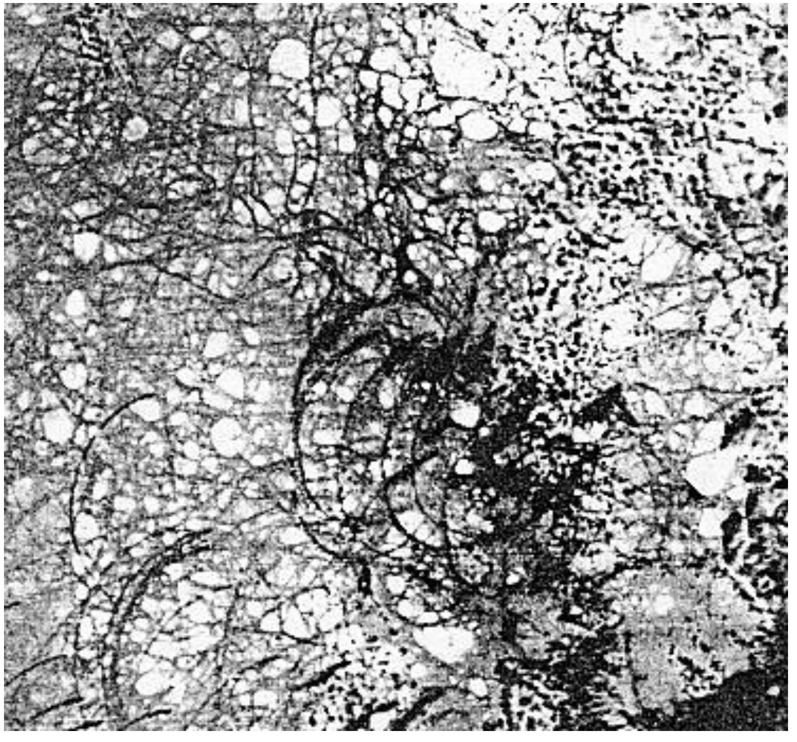
Circulation patterns and tidal effects



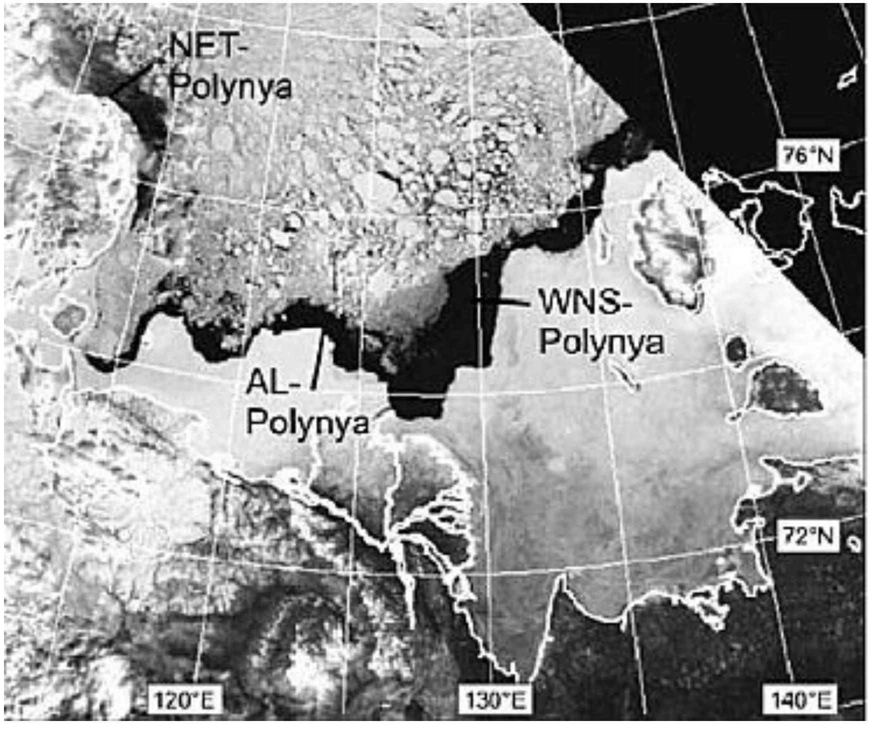


Holloway, G., and A. Proshutinsky (2007), Role of tides in Arctic ocean/ice climate, J. Geophys. Res., 112, C04S06, doi:10.1029/2006JC003643.

Manifestations of tidal ice drift in the Arctic Ocean

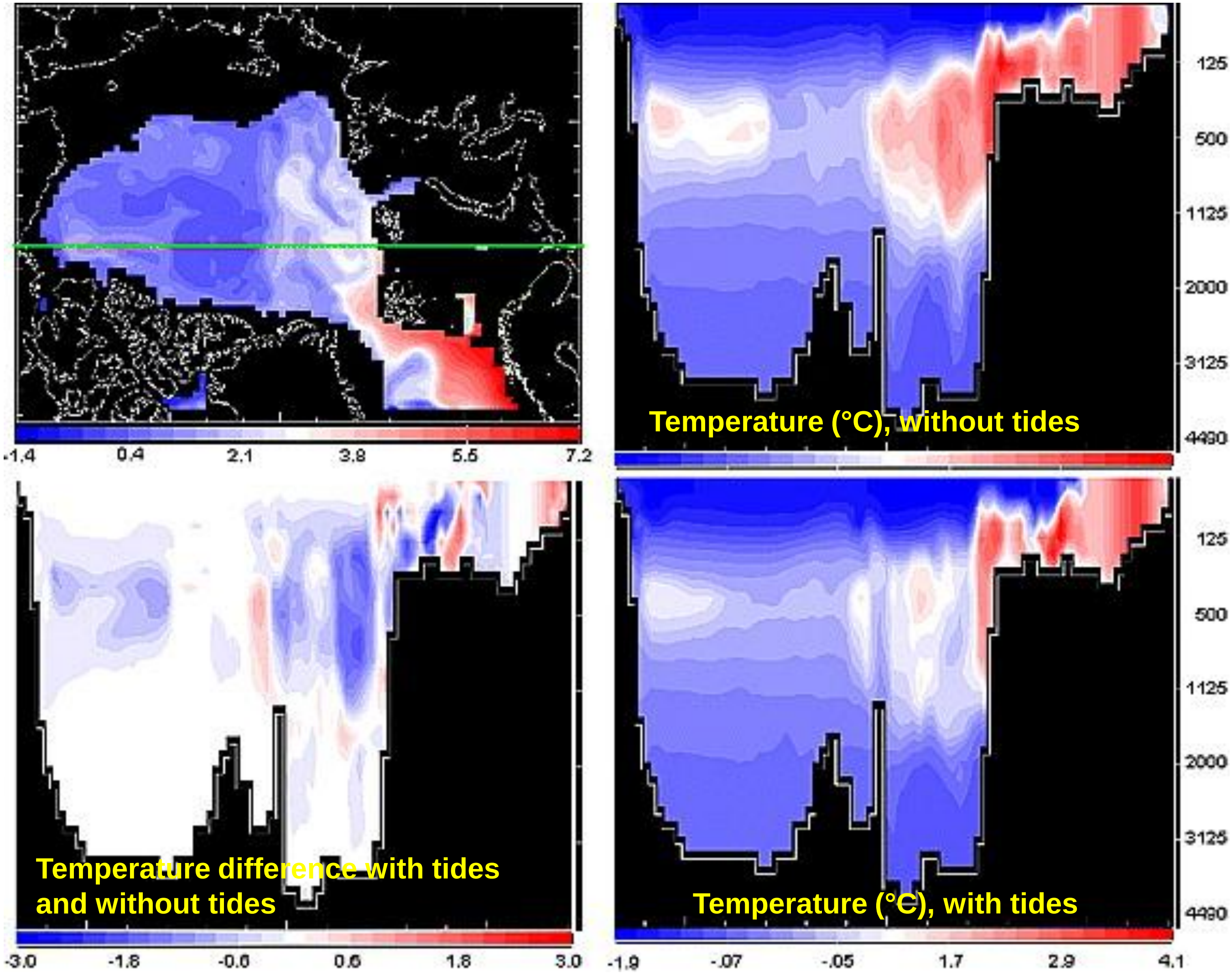


Satellite image of ice cover in the vicinity of Spitsbergen on June 1, 1988, from Dmitriev et al. [1991] with permission from Polar Research. Elliptically shaped leads are formed behind grounded icebergs as sea ice is driven by tidal currents.



NOAA AVHRR image (visible channel) of the Laptev Sea polynyas (Great Siberian Polynya) on 3 June 1995; adapted for this paper from Bareiss and Gorgen [2005] with permission from Elsevier. The main flaw polynyas as parts of the Great Siberian Polynya are: Northeastern Taimyr Polynya (NET), Anabar-Lena Polynya (AL), West New Siberian Polynya (WNS) and East Severnaya Zemlya Polynya

Holloway, G., and A. Proshutinsky (2007), Role of tides in Arctic ocean/ice climate, J. Geophys. Res., 112, C04S06, doi:10.1029/2006JC003643.



Holloway, G., and A. Proshutinsky (2007), Role of tides in Arctic ocean/ice climate, J. Geophys. Res., 112, C04S06,

doi:10.1029/2006JC003643.

Upper left: Potential temperature (°C) is shown at 320 m during December 1999 from a case without tides.

Upper right: Temperature (°C), without tides, is shown on the vertical section marked by a green bar in the upper left panel.

Lower right: Temperature (°C) is shown on the same vertical section, with the same color scale, as upper right but here including effects of tides

Lower left: The difference of temperature (°C) with tides and without tides

Tidal effect results

- Results show tides enhancing loss of heat from Atlantic waters.

- The impact of tides on sea ice is more subtle as thinning due to enhanced ocean heat flux competes with net ice growth during rapid openings and closings of tidal leads.

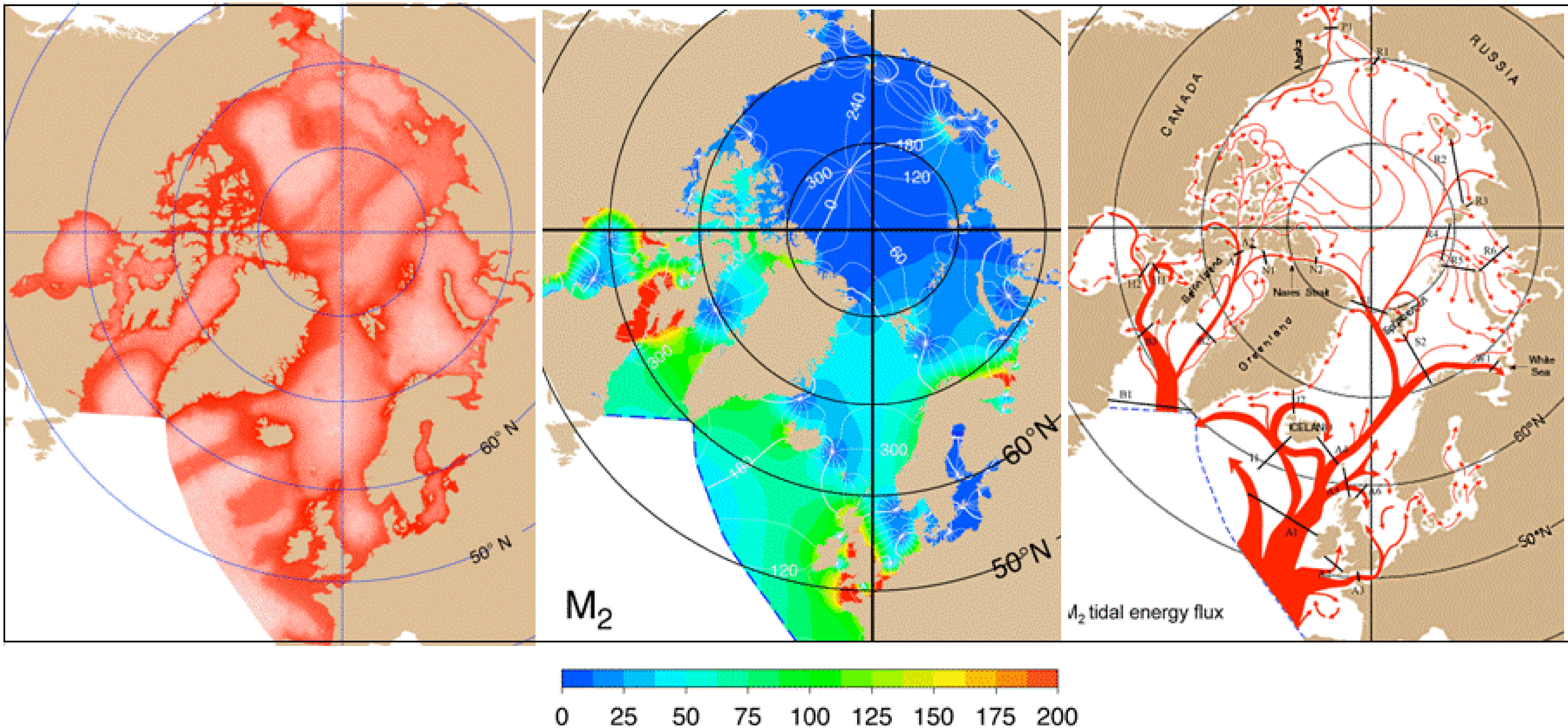
- Among results from AOMIP is a tendency for models to accumulate excessive Arctic Ocean heat throughout the intercomparison period 1950 to 2000 which is contrary to observations. Tidally induced ventilation of ocean heat reduces this discrepancy.

Current tidal work:

❖Several AOMIP groups have been involved in tidal experiments, at the initial stage via implementing tides in their models. A spherical coordinate version of the unstructured grid 3-D FVCOM (finite volume coastal ocean model, Chen et al., 2009) has been applied to the Arctic Ocean to simulate tides with a horizontal resolution ranging from 1 km in the near-coastal areas to 15 km in the deep ocean.

❖This model has reproduced very well the diurnal and semidiurnal tidal wave dynamics and captures the complex tidal structure along the coast, particularly in the narrow straits of the Canadian Archipelago.

❖Experiments with running this model under realistic forcing and tides are under design now and we expect that inclusion of tides will allow us to better understand their role in the dynamics and hydrographic structure of the Arctic Ocean.



Left: Unstructured triangular grid of AO-FVCOM for the Arctic Ocean. Total numbers of triangular cells and nodes are 520,817 and 275,574. The horizontal resolution (measured by the side length of each triangle) varies from 1 to 3 km in the Canadian Archipelago, inlets and straits, and over the shelf break to 10–15 km in the interior basins. Middle: The model-predicted M2 cotidal charts. The color image represents the tidal amplitude (cm) and contours. From Chen et al. [2009].

Modeling with data assimilation

There are several AOMIP modeling teams who are involved in modeling with data assimilation:

UW: J. Zhang (sea ice) PAOSIM
MIT: P. Heimbach (ECCO2)
AWI: F. Kauker and M. Karcher (NAOSIM)
IARC: G. Panteleev (

Collaborative Research: Toward reanalysis of the Arctic Climate System—sea ice and ocean reconstruction with data assimilation

Principal Investigators:

A. Proshutinsky, **Woods Hole Oceanographic Institution**

D. Nechaev, ***University of Southern Mississippi***

G. Panteleev, ***International Arctic Research Center***

J. Zhang and R. Lindsay, ***University of Washington***

Synthesis of Arctic System Science Workshop, Alexandria, VA
October 2 – 4, 2007

Objectives

- **Develop an integrated set of assimilation procedures for the ice–ocean system**

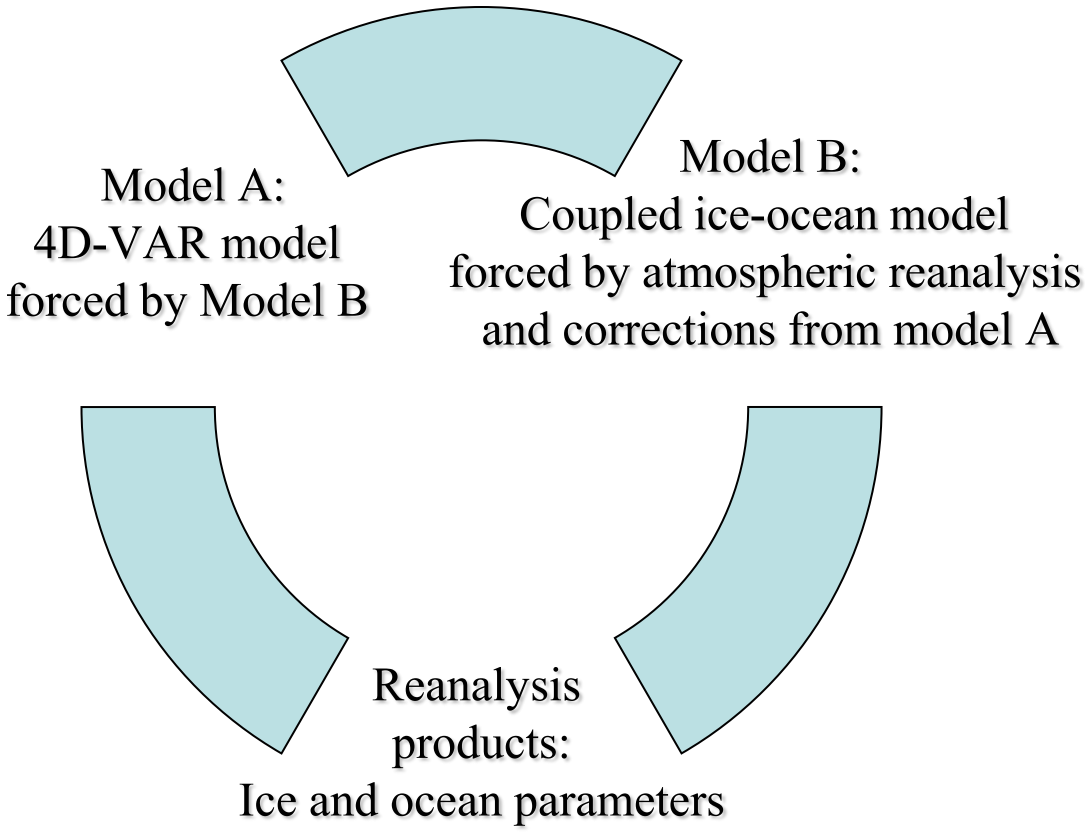
- **Validate the system performance, assess the quality of the major system products, and provide the community with gridded sea ice and ocean parameters**

- **Investigate arctic system variability and the processes important for causing the observed changes based on the reanalysis products.**

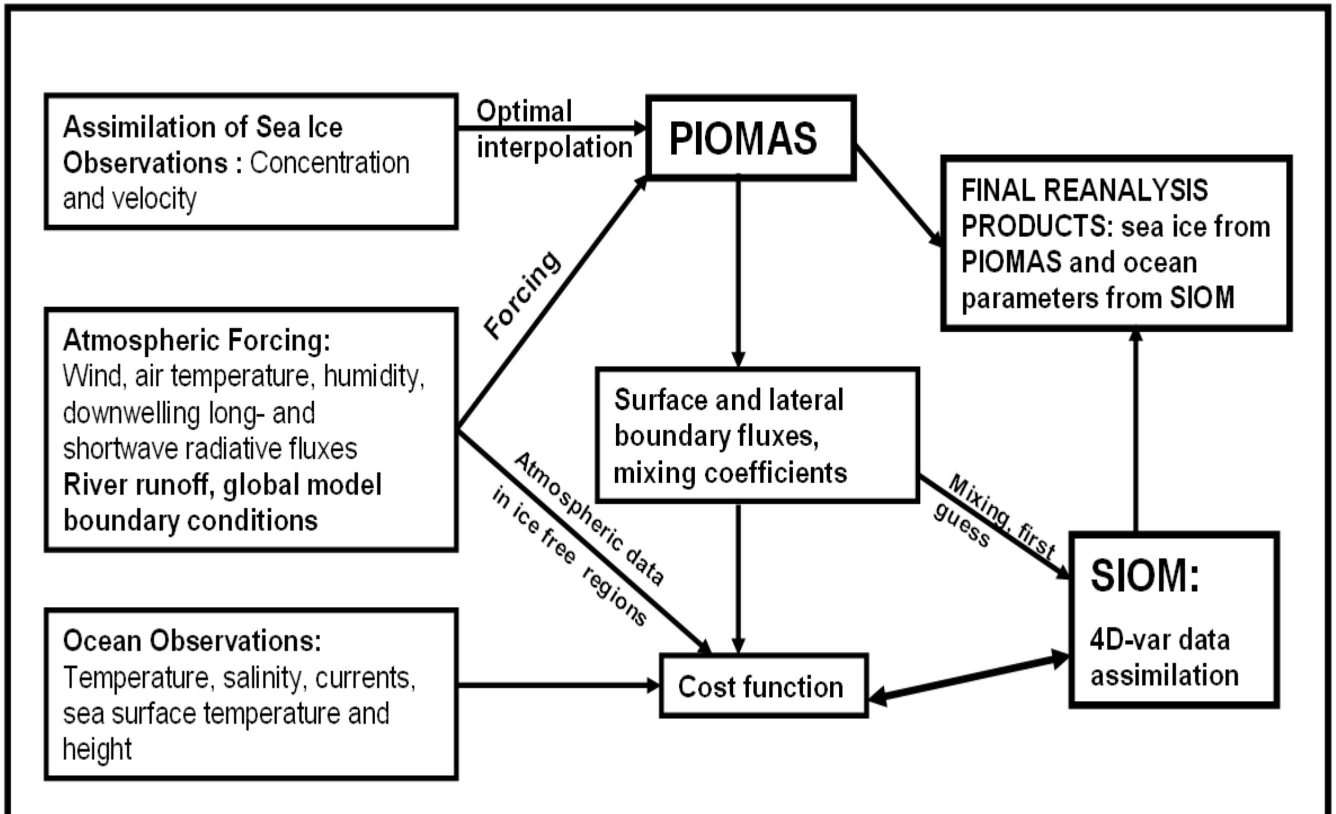
Approach

Existing conventional methods of oceanic modeling with data assimilation do not have algorithms for the coupled ice-ocean systems.

In order to reach project goals we have developed an approach based on employing of two models. Model “A” uses a conventional Four Dimensional Variational (4D-VAR) technique. It does not have sea ice but uses all needed information from model “B” which is a regional coupled ice-ocean model. The B model is forced by atmospheric reanalysis fields and corrects its forcing based on data obtained from model “A”.

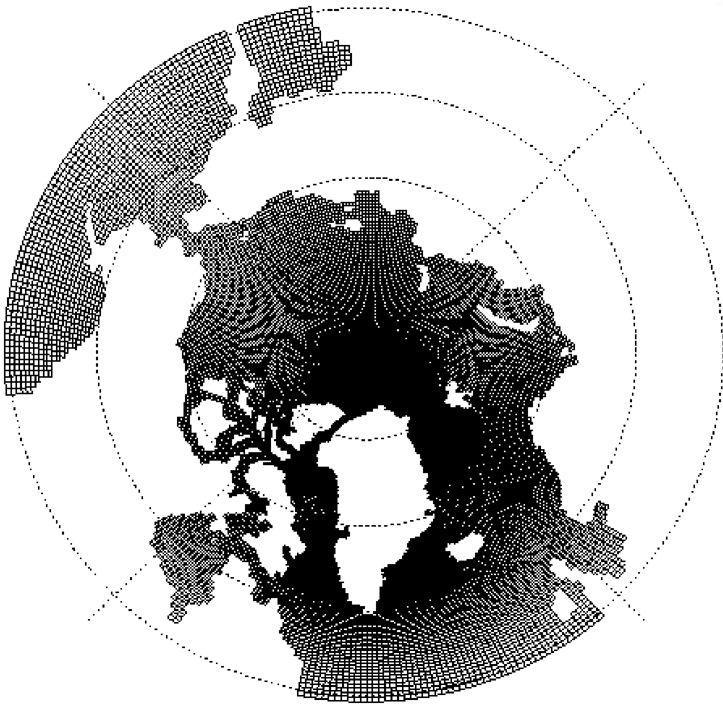


Data flow chart for the data assimilation procedure “a”.

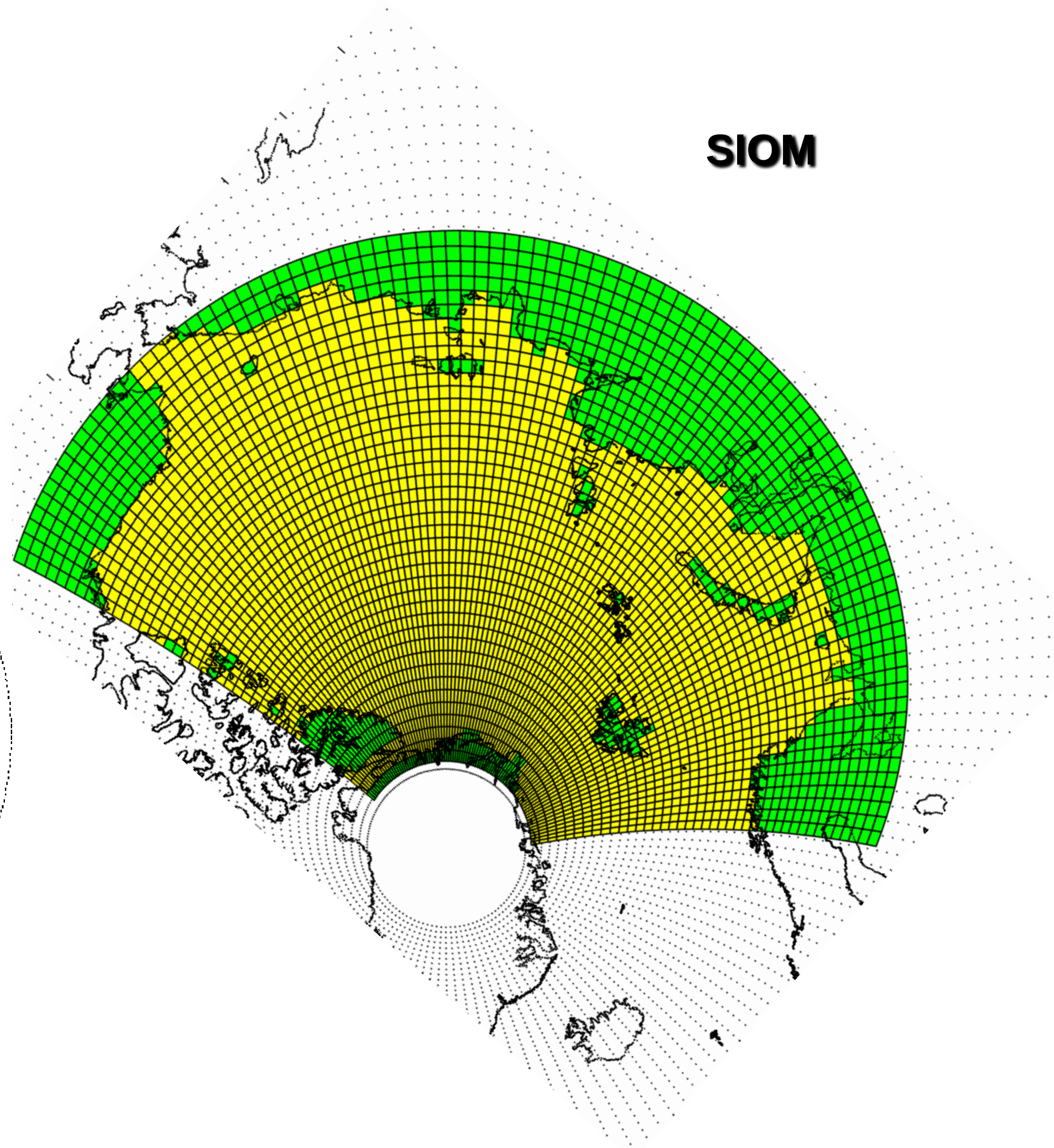


Model Domains

PIOMAS



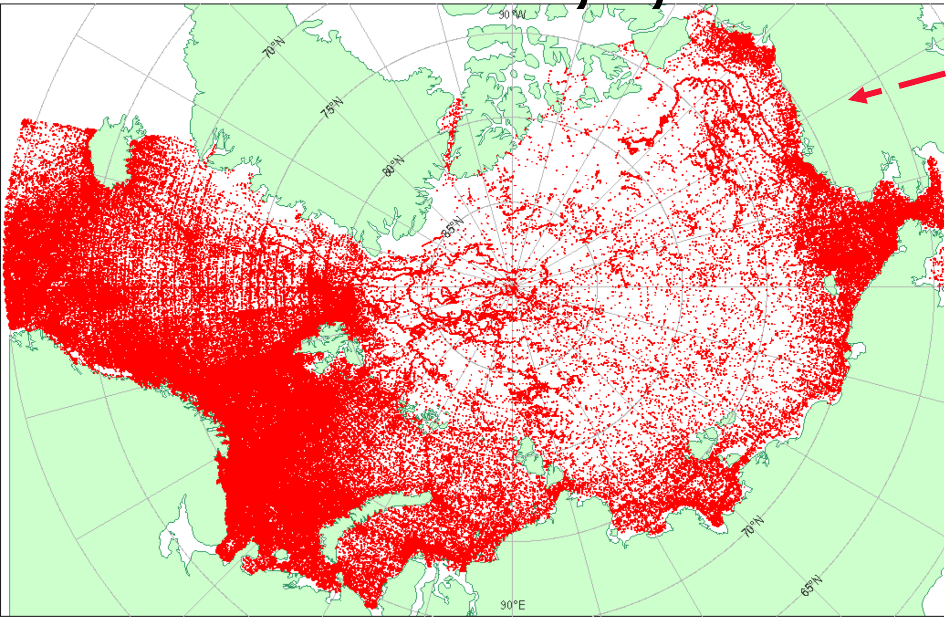
SIOM

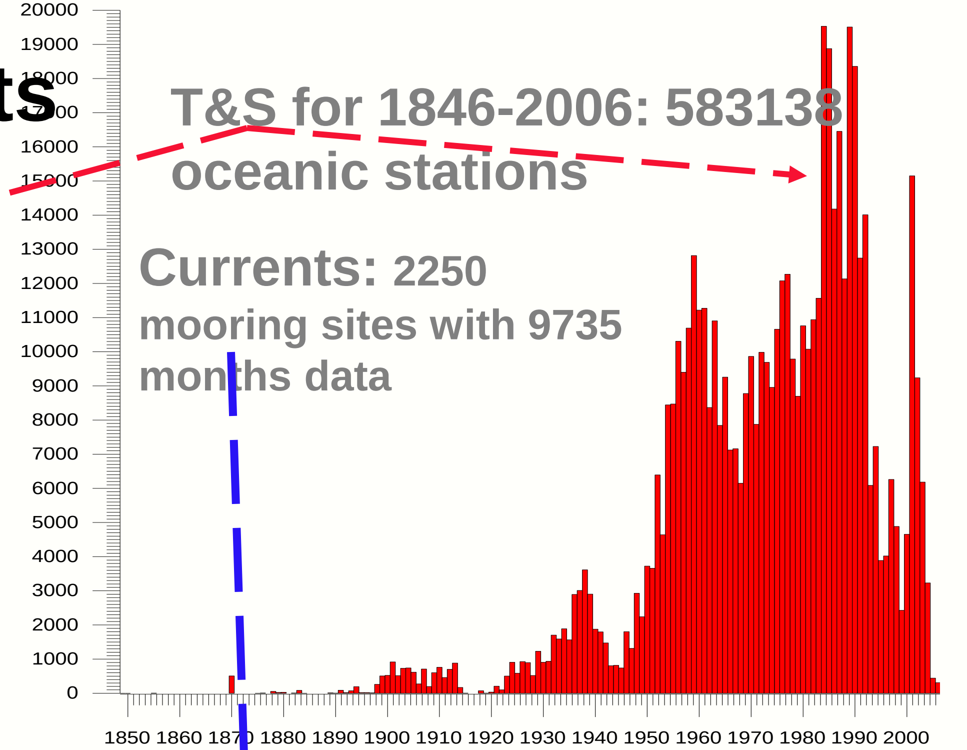


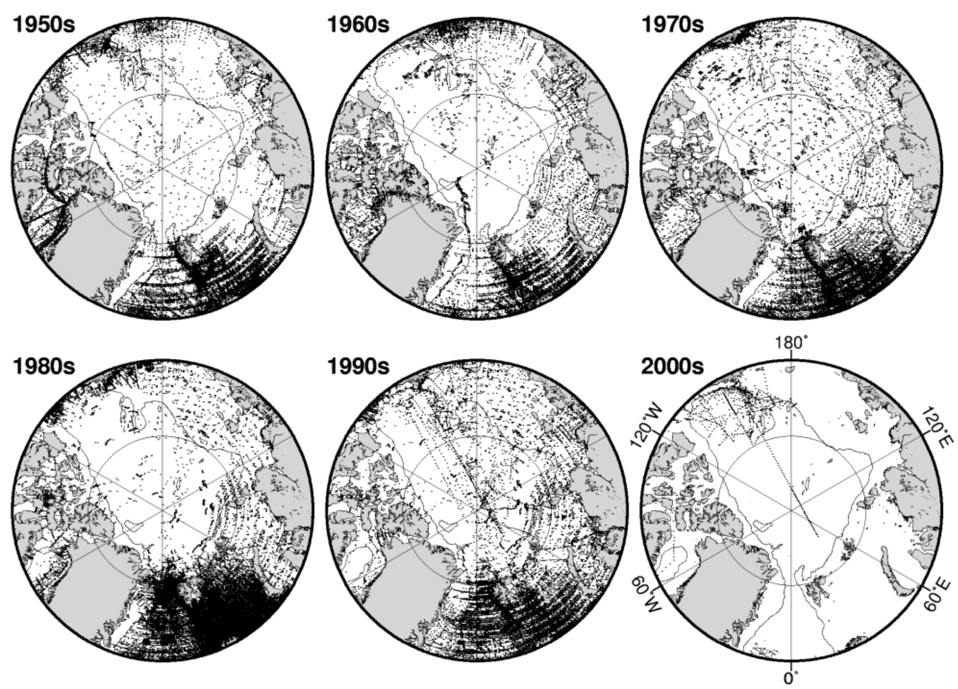
Ocean data: T,S, currents

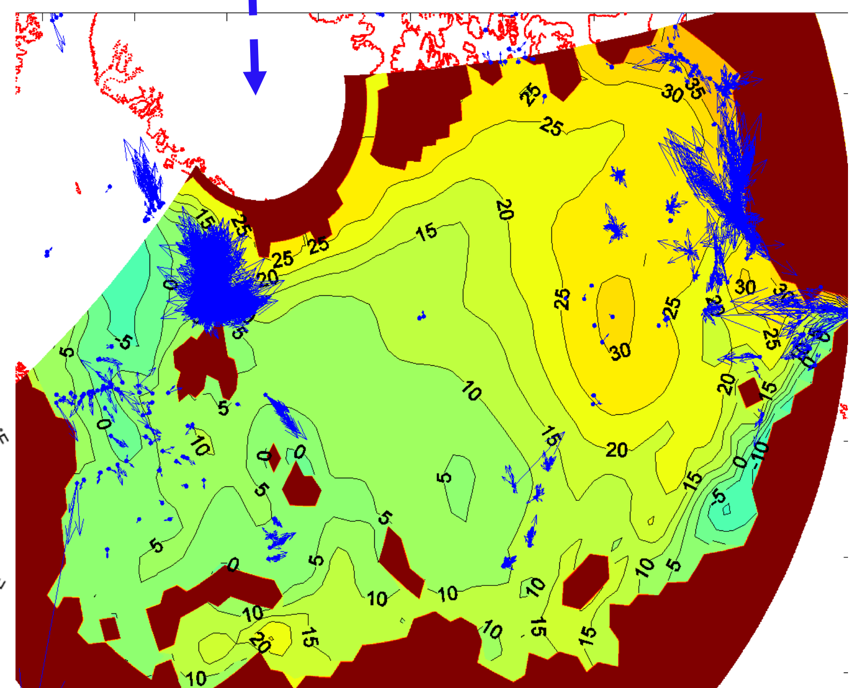
T&S for 1846-2006: 583138 oceanic stations

Currents: 2250 mooring sites with 9735 months data

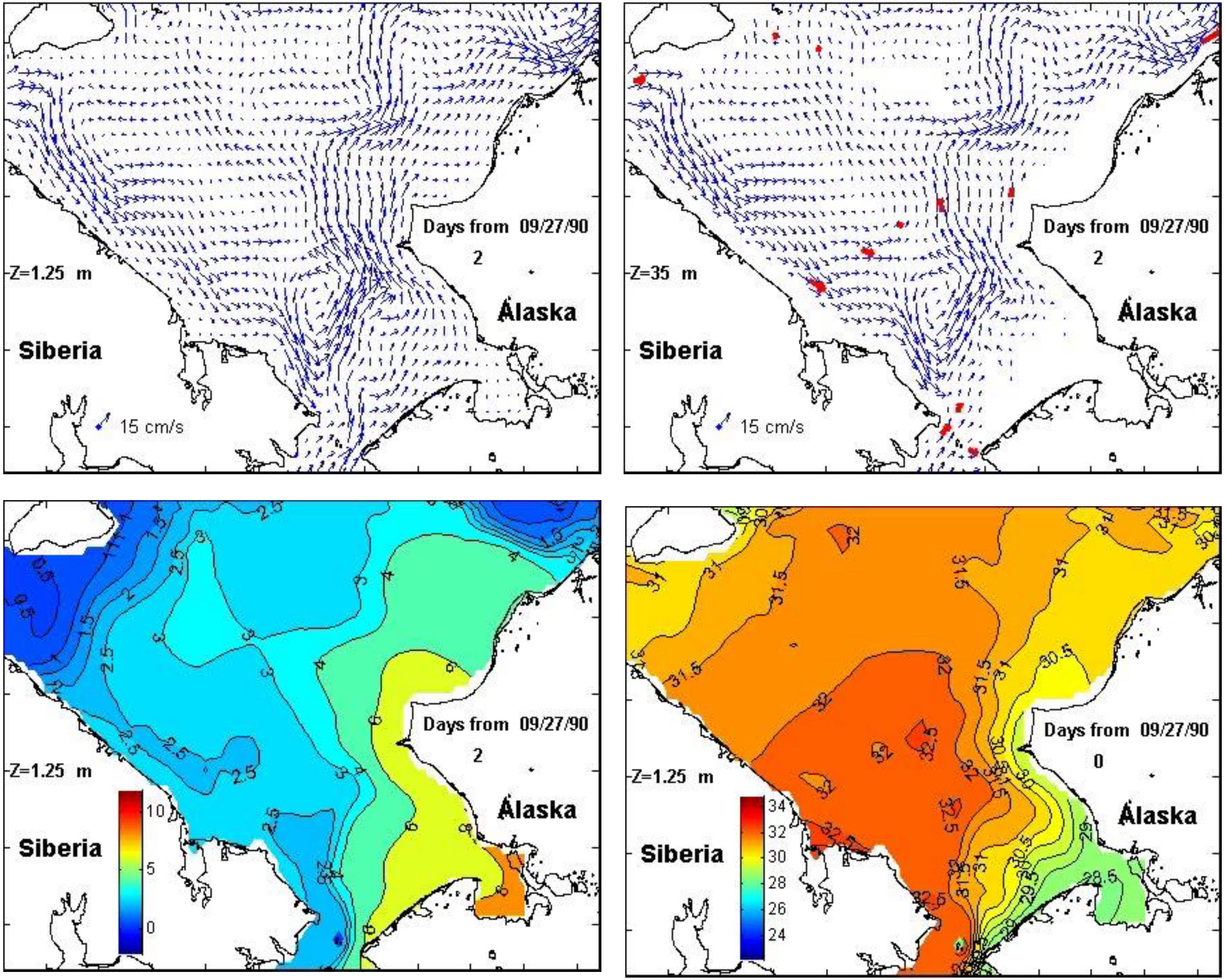




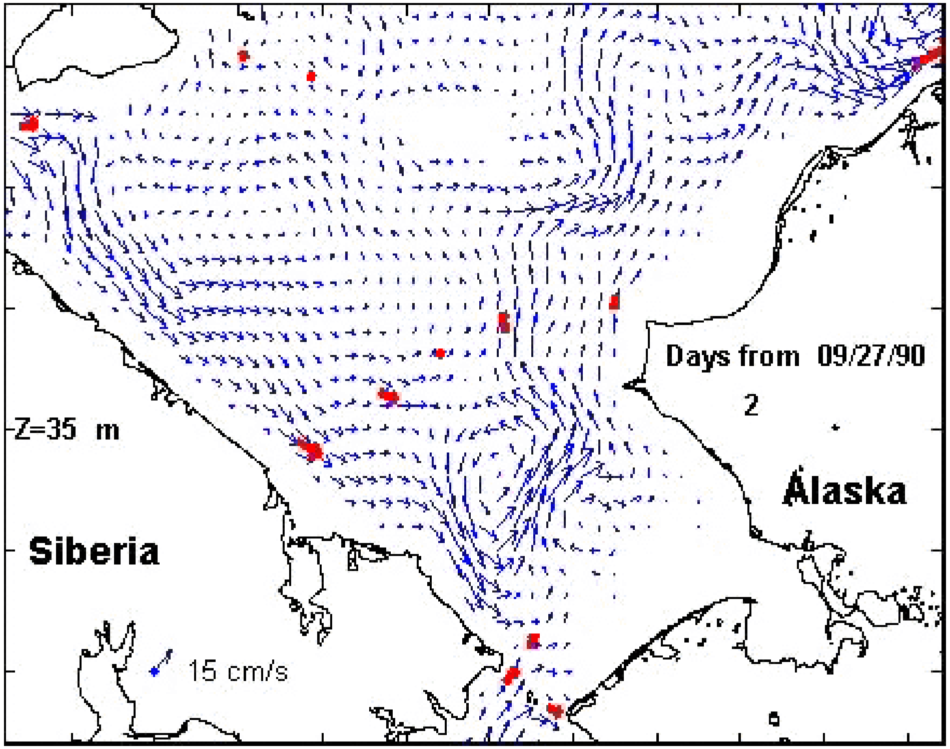




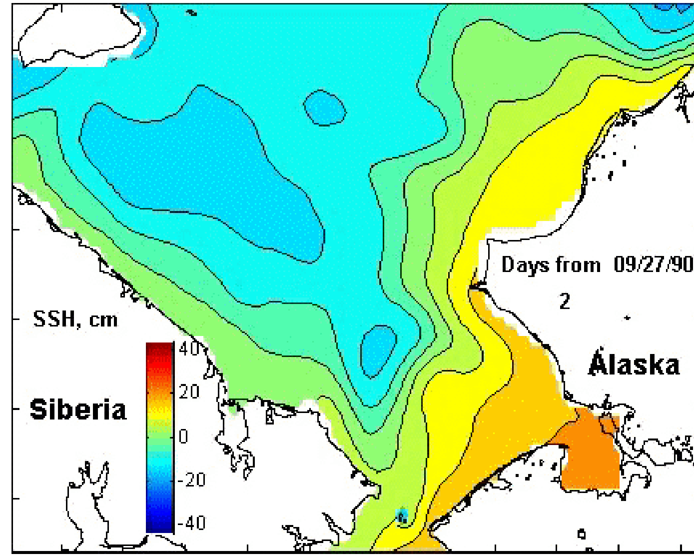
Reanalysis (hindcast) of the fall 1990 circulation in the Chukchi Sea



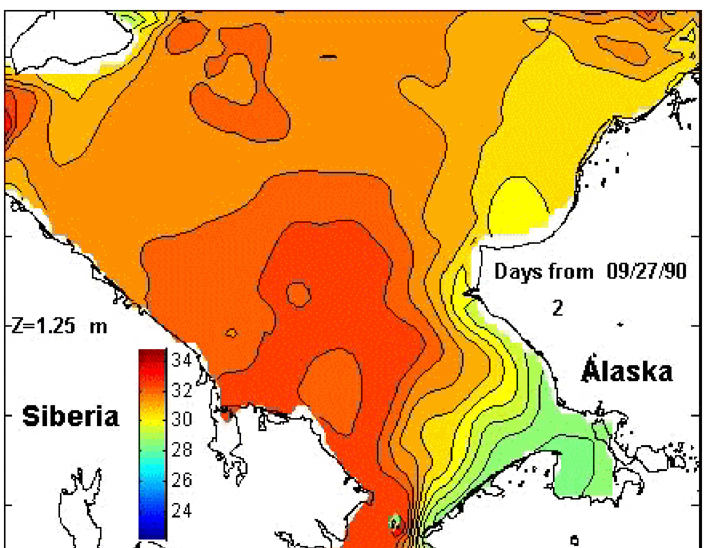
1) Reverse of the Bering Strait current.
2) Reverse of the East Siberian current and inflow of fresh/cold water from East Siberian Sea
3) Very good agreement between mooring measurements due to very high controllability through the boundary conditions



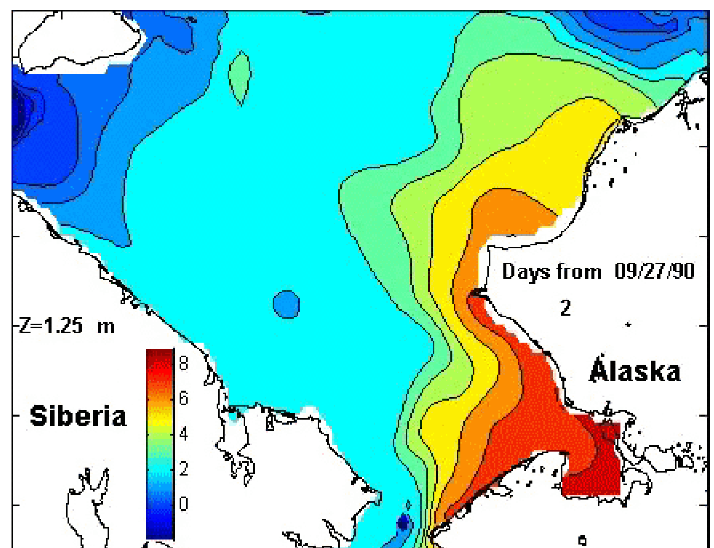
Days from 09/27/90
2
Z=35 m
Alaska
Siberia
15 cm/s



Days from 09/27/90
2
SSH, cm
40
20
0
-20
-40
Alaska
Siberia



Days from 09/27/90
2
Z=1.25 m
34
32
30
28
26
24
Alaska
Siberia



Days from 09/27/90
2
Z=1.25 m
8
6
4
2
0
Alaska
Siberia

Model improvements recommendations:

Some of these recommendations are common for all Arctic models and may be termed trivial, but they nevertheless need serious attention, namely, increasing model resolution, improving initial and boundary conditions, establishing initialization techniques for seasonal and decadal prediction systems, and enhancing forcing.

These recommendations — except for the one to increase model resolution — could be implemented by increasing the quantity and quality of observations and improving data assimilation methods.

Model improvements recommendations:

❖ Coupled ice-ocean models have problems with restoring and flux correction procedures, and this limits the models' "natural" variability caused by forcing, the models' physics, and the models' errors due to the problems with numerical representation of model equations. It is important to overcome these problems by improving model forcing and internal model parameters based on observations.

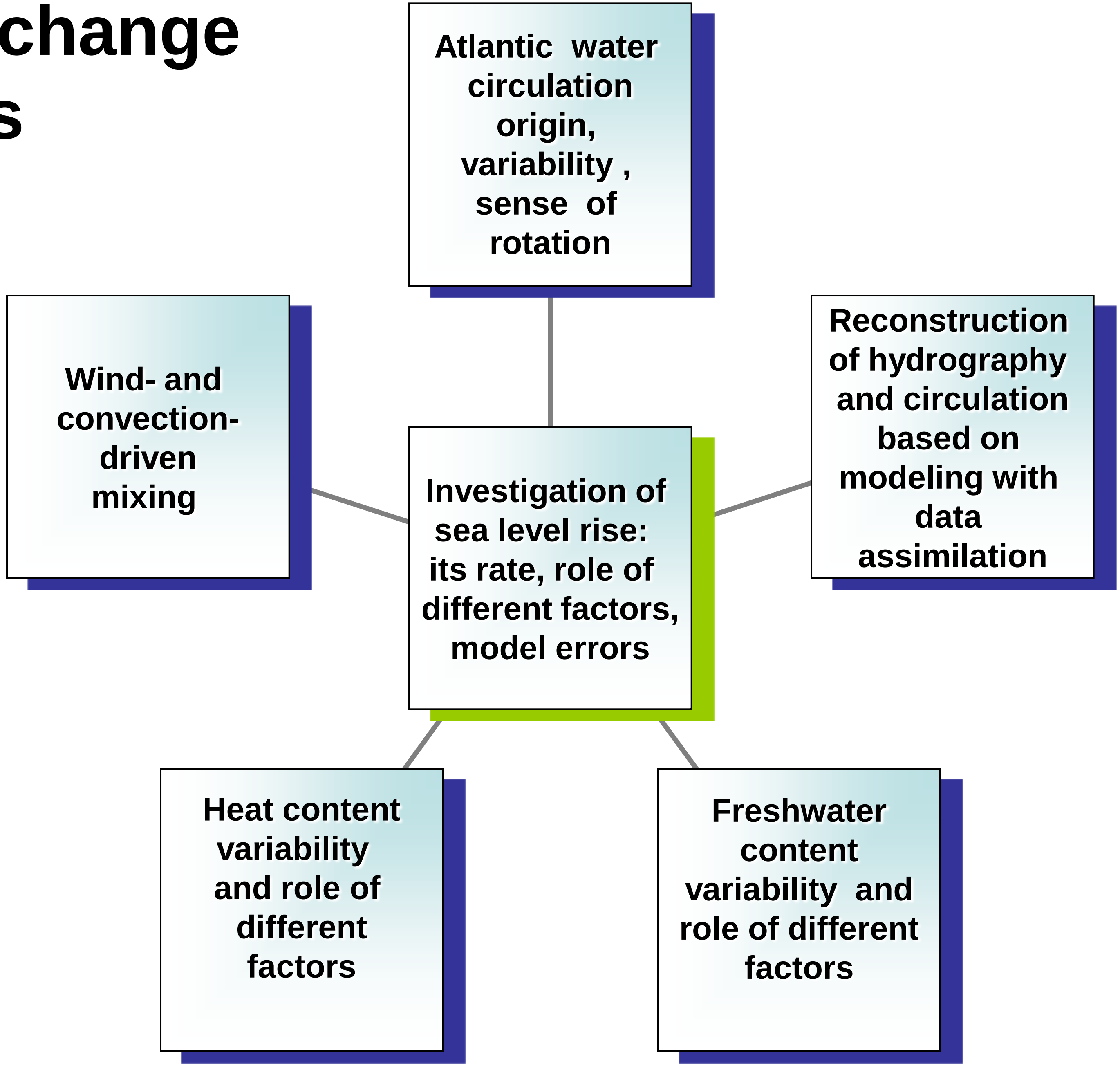
❖ Processes of vertical and lateral mixing and the parameterization of eddies, plumes, freshwater and heat fluxes, the cold shallow halocline, and brine formation also require refinement and validation.

❖ With the increase in model horizontal resolution, sea ice dynamics and thermodynamics must be improved toward (1) a better description of small-scale processes and deformations and (2) the introduction of forcing at inertial and tidal frequencies. Frazil ice (initial stage of sea ice) formation and land-fast ice (which forms and remains fast along the coast) development and decay have to be taken into account as well.

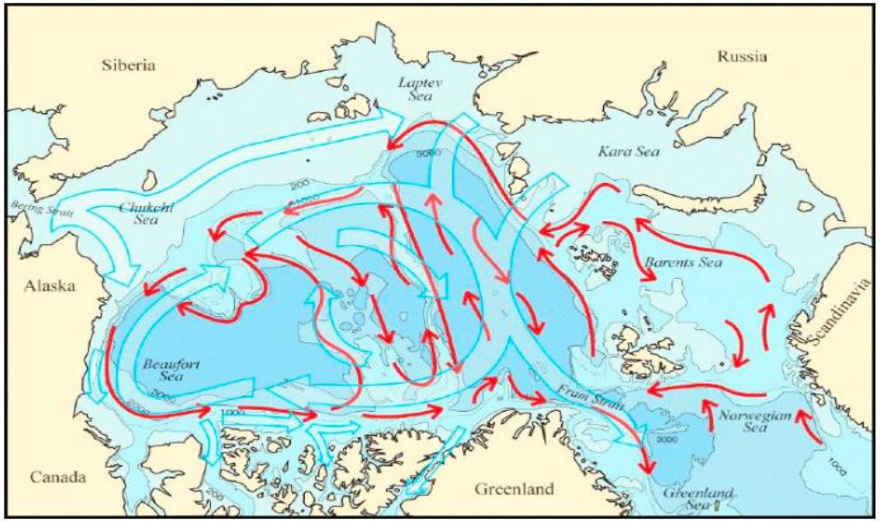
Model improvements recommendations:

- Tidal forcing is important for Arctic Ocean modeling;
- Tidal and inertial dynamics has to be included in the sea ice models as well;
- Inverted barometer effect is an important component for simulations of synoptic variability;
- Variable river runoff and Bering Strait inflow are important parameters influencing Arctic climate and have to be taken into account;
- Land-fast ice is an important regulator of dynamics and thermodynamics because it influences upwelling and downwelling, sea ice production and brine rejection, shelf water properties.

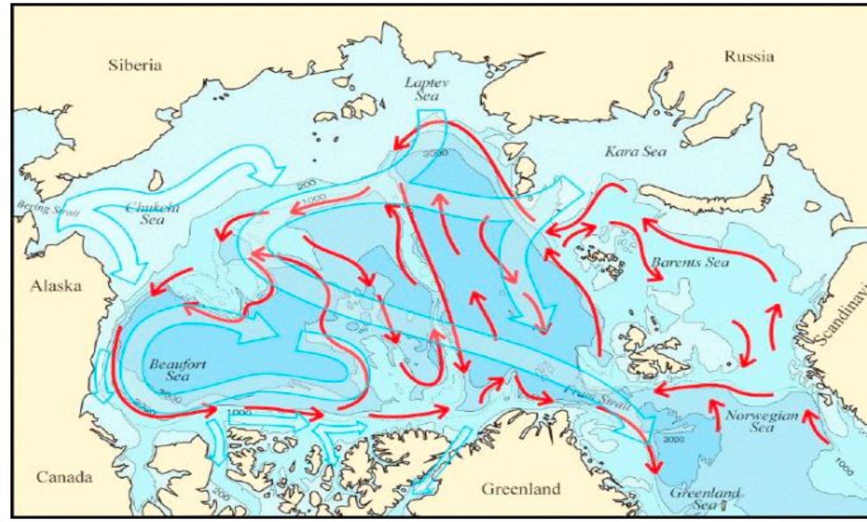
Arctic change studies



Atlantic Water circulation



Two conceptual diagrams elaborate. Caution: beware artistic license! Upper layer flows are shown as light blue; subsurface (and sometimes surface) flows are in red.

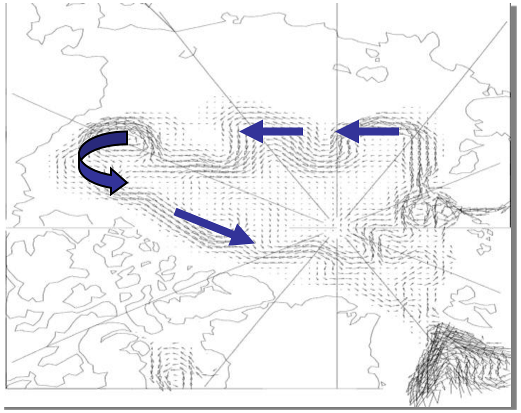


Although upper layer circulation varies, from largely anticyclonic to more cyclonic, these sketches suggest the subsurface flows hardly change at all!

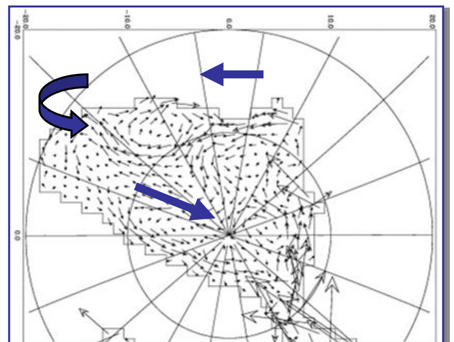
There are several scientific questions associated with the origin, direction, and variability of the Atlantic water layer circulation in the Arctic Ocean. Observational studies suggest that this circulation is cyclonic and its intensity may change depending on Arctic Oscillation or North Atlantic Oscillation regime. How surface forced ocean regulates circulation in deep layers is not clear. Figures above suggest that deep circulation does not change significantly when surface circulation changes from anticyclonic to cyclonic.

Models with cyclonic circulation of Atlantic water

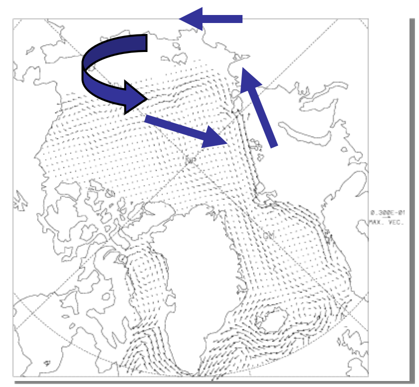
MOM high resolution



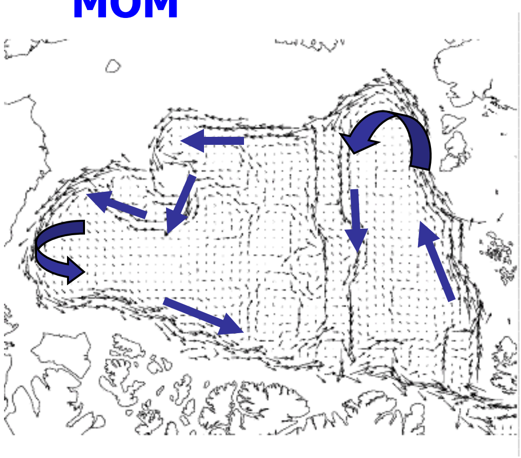
MOM low resolution



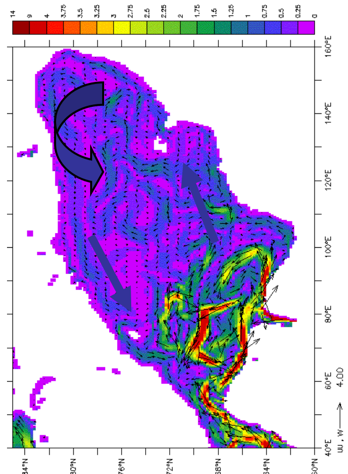
POM



MOM



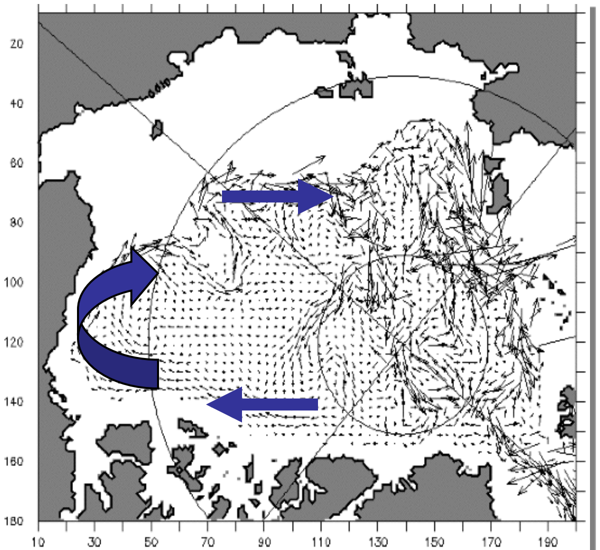
Global, OPA



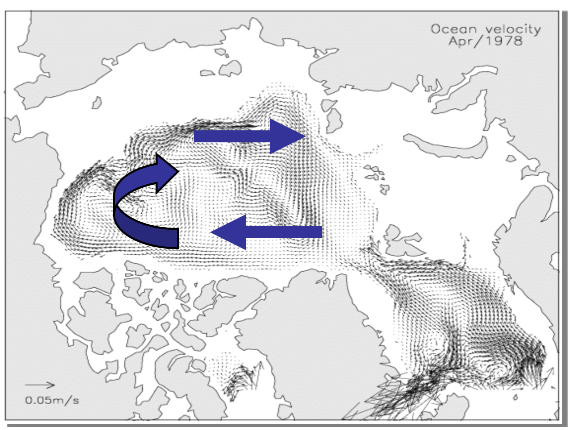
AOMIP studies showed that some models generate cyclonic circulation which intensity changes in time insignificantly. Other model results show that circulation changes and even may reverse its direction. What is the origin of these reversals?

Models with anticyclonic circulation of Atlantic layer

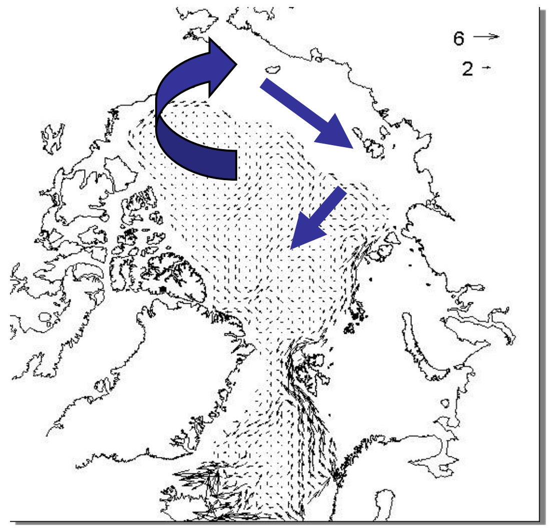
MOM high resolution



MOM

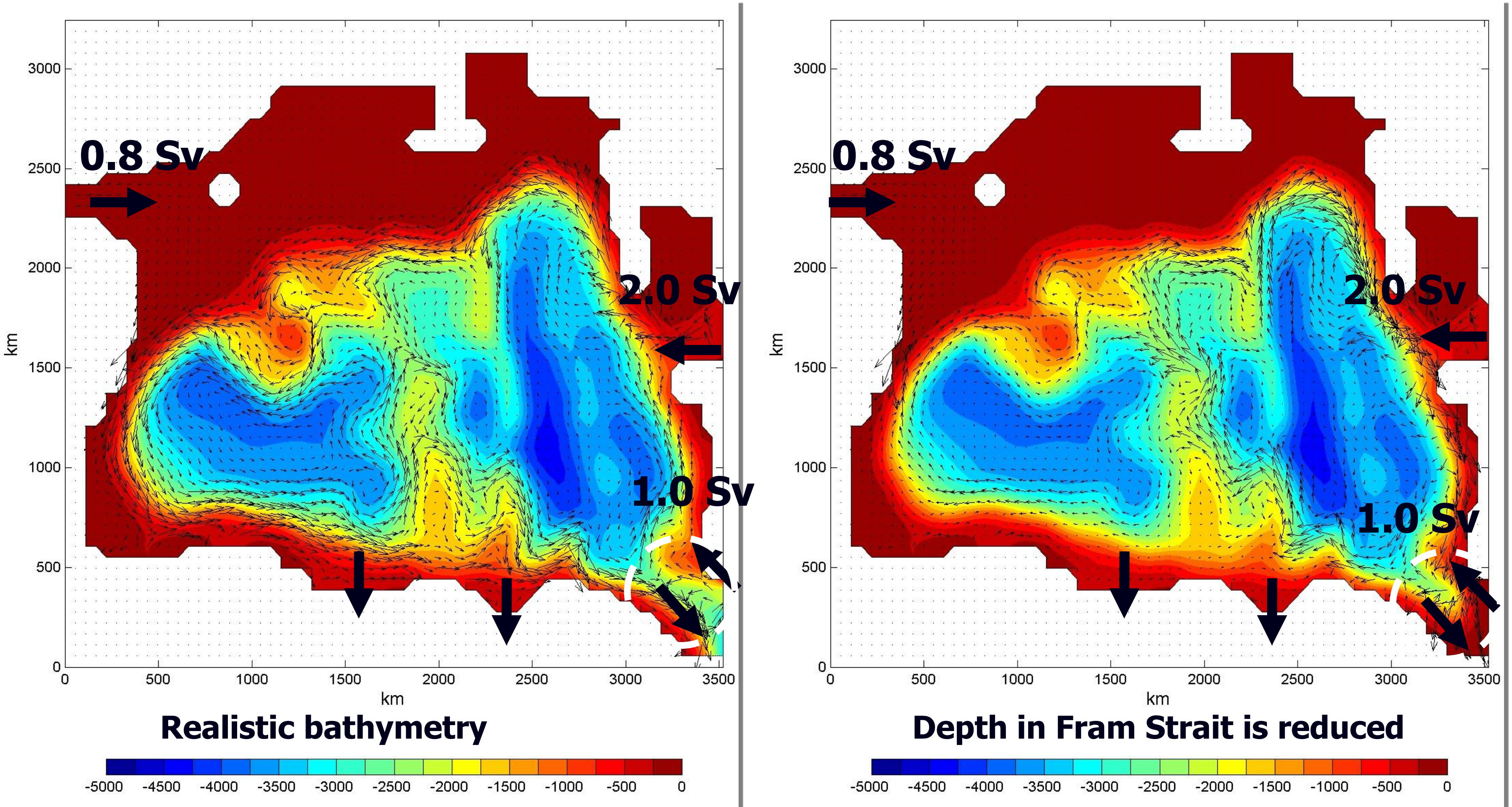


Finite elements



Several models showed that the Atlantic water circulation is very stable and is anticyclonic!!! Note that model forcing, initial conditions, bathymetry, etc. were identical in the models reproduced cyclonic and anticyclonic motion of the Atlantic water.

AOMIP theoretical studies and numerical experiments show that circulation regime of Atlantic layer may depend on boundary conditions and due to potential vorticity constraints it can change from cyclonic to anticyclonic and could be regulated by the AO or NAO.



Circulation and potential vorticity (courtesy of Jiayan Yang, WHOI)

Major 2008-2010 activities

1. **Workshops:**

- 12^{th} – January 2009 (24 participants)
- 13^{th} – October 2009 (49 participants) and AOMIP school for young scientists (14)
- 14^{th} – October 2010 (97 participants) and AOMIP school for young scientists (35)

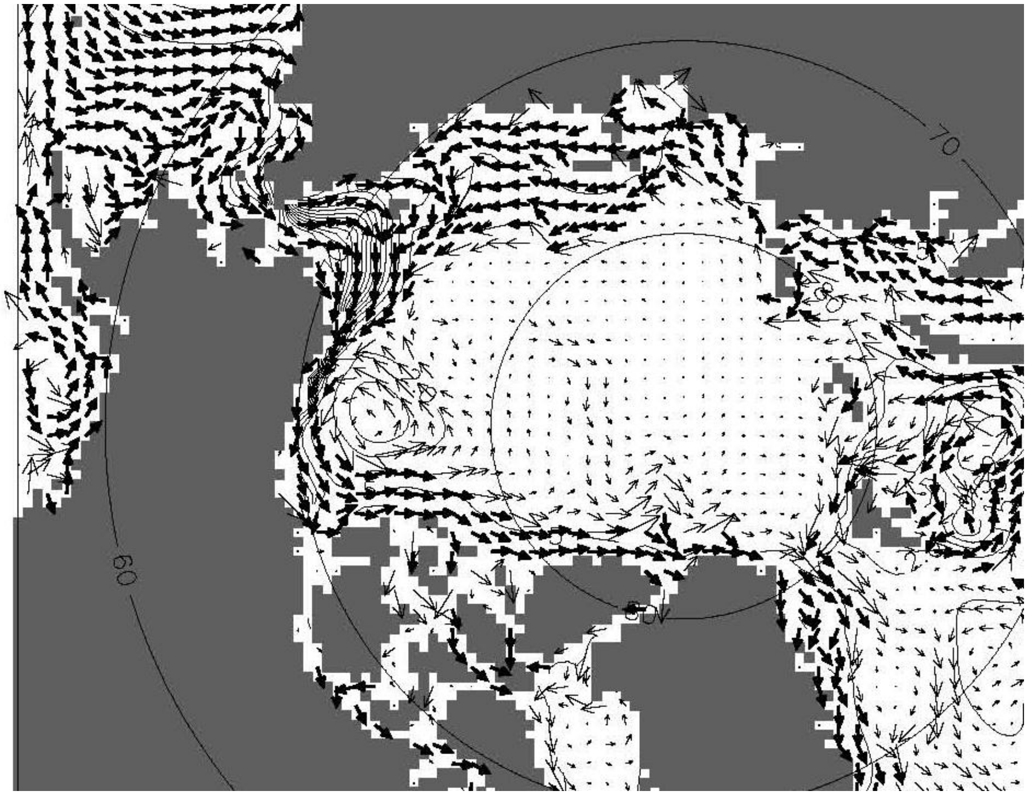
Major 2008-2011 activities

2. **Coordinated experiments/themes**

- **Bering Strait volume, heat and salt fluxes**
- **Canada Basin: shelf-basin exchange and mechanisms**
- **Pacific Water circulation (origin, forcing, pathways)**
- **Canada Basin: major mechanisms of halocline formation and variability**
- **Circulation and fate of fresh water from river runoff**
- **Beaufort Gyre: mechanisms of fresh water accumulation and release**
- **Fresh water balance of the Arctic Ocean**
- **Atlantic Water circulation**
- **Ecosystem experiments**
- **Observations, state estimation, and adjoint methods**

Coordinated experiments

Bering Strait volume, heat and salt fluxes: **J. C. Kinney, W. Maslowski, M. Steele, R. Woodgate et al.**



This is a collaborative model-observational study of volume, heat, and freshwater fluxes through Bering Strait, an important arctic gateway. This experiment focuses on this strait because of its physical importance for the Arctic Ocean ice and water dynamics and thermodynamics. A set of numerical experiments and model intercomparisons seeks to answer a series of important scientific questions, validate Arctic regional and global models using Bering Strait historical and recently collected data, and to recommend important model improvements allowing reproduction of the Bering Strait – related changes in the entire Arctic Ocean.

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

NSF

Coordinated experiments

Bering Strait volume, heat and salt fluxes: **J. C. Kinney, W. Maslowski, M. Steele, R. Woodgate et al.**

This is a collaborative model-observational study of volume, heat, and freshwater fluxes through Bering Strait, an important arctic gateway. This experiment focuses on this strait because of its physical importance for the Arctic Ocean ice and water dynamics and thermodynamics. A set of numerical experiments and model intercomparisons seeks to answer a series of important scientific questions, validate Arctic regional and global models using Bering Strait historical and recently collected data, and to recommend important model improvements allowing reproduction of the Bering Strait – related changes in the entire Arctic Ocean.

Coordinated experiments

***Circulation and fate of fresh water from river runoff (pathways and seasonal transformation due to mixing and freezing)*: Ye. Aksenov, A. Jahn, E. Golubeva, G. Platov et al.**

A relatively recently published paper "Sensitivity of the thermohaline circulation to Arctic Ocean runoff" by Rennermalm et al (2006) investigates how changes in Arctic river discharge may control thermohaline circulation by a series of experiments with an intermediate complexity global climate and regional models. The study does not, however, study how the arctic river runoff reaches the North Atlantic and how much time it takes for this water to influence the THC. This study will fill this gap and will answer a set of scientific questions about pathways of river water and its transformations.

Coordinated experiments

Canada Basin: shelf-basin exchange and mechanisms:
E. Watanabe, G. Nurser, W. Maslowski, et al.

The major science questions for these experiments are:

(1) How much of the heat and fresh water associated with the Pacific Water are transported from the Chukchi shelf to the Canada Basin across the Beaufort shelf break by meso-scale eddies?

(2) What are the mechanisms controlling generation and development of meso-scale eddies which are thought to play an important role in the shelf-basin mass, heat and fresh water exchanges

Coordinated experiments

Beaufort Gyre: mechanisms of fresh water accumulation and release: **A. Proshutinsky, W. Hibler, E. Watanabe et al.**

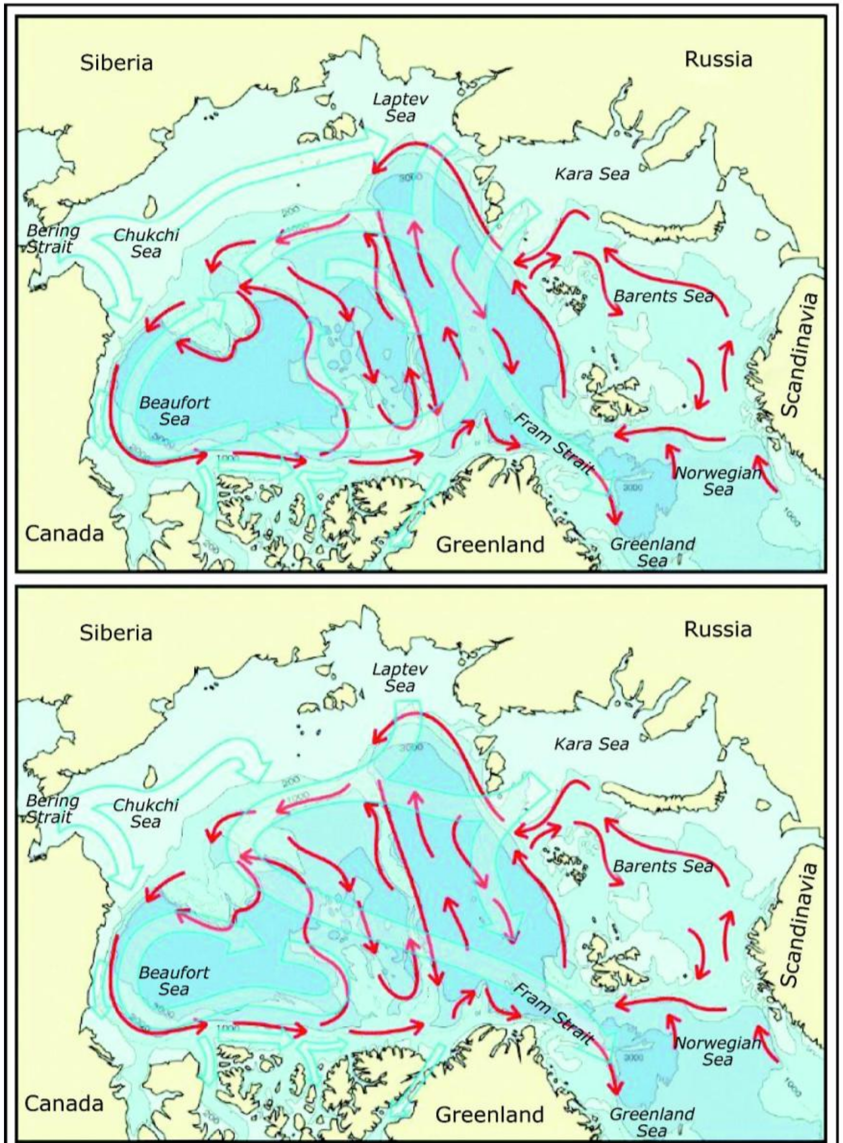
Hydrographic climatology shows that due to a salinity minimum which extends from the surface to approximately 400m depth, the Canada Basin contains about 45,000 km3 of fresh water. It was shown that Ekman pumping can be responsible for this fresh water reservoir in the center of Canada Basin of the Arctic Ocean (Proshutinsky et al. 2002). The interplay between dynamic- and thermodynamic forcing is undoubtedly complex. This problem is under investigation by AOMIP via coordinated experiments specifically designed to understand the major mechanisms of fresh water accumulation and release in the BG Region. Two experiments were conducted investigating roles of wind induced Ekman pumping and seasonal transformations of sea ice and river discharges.

Coordinated experiments

Fresh water balance of the Arctic Ocean: seasonal and interannual variability (sources, sinks, pathways): **A. Jahn, R. Gerdes, A. Nguyen, Ye. Aksenov, W. Maslowski, C. Herbaut et al.**

This research attempts to answer the fundamental questions: How does fresh water enter the Arctic Ocean system? How does it move about including undergoing phase changes? How does it finally exit the system? AOMIP groups responsible for this activity evaluate how well models reproduce pan-Arctic freshwater budget by comparison of model outputs with observed estimates. It is anticipated that most (but perhaps not all) models will achieve freshwater balance in the oceanic upper layers. How these balances are actually achieved will provide insight into model physics.

Coordinated experiments



Atlantic Water circulation (circulation patterns, variability and heat exchange, model validation based on observations): **R. Gerdes**, Ye. Aksenov, A. Nguyen, W. Maslowski, C. Postlethwaite, R. Gerdes

The cyclonic pattern of Atlantic water propagation along the continental slope, proposed by Rudels *et al.* (1994) is supported by some numerical models (Holland, Karcher, Holloway, AOMIP*, pers. com.*). However other models (Häkkinen, Maslowski, Zhang, AOMIP*, pers. com.*) show anticyclonic rotation of this “wheel”. McLauglin *et al*., (2004) showed that Atlantic Water as much as 0.5°C warmer than the historical record were observed in the eastern Canada Basin relatively recently. These observations signaled that warm-anomaly Fram Strait waters, first observed upstream in the Nansen Basin in 1990, had arrived in the Canada Basin.

Coordinated experiments

Atlantic Water circulation (circulation patterns, variability and heat exchange, model validation based on observations): **R. Gerdes, Ye. Aksenov, A. Nguyen, W. Maslowski, et al.**

The mechanisms that drive the mean and time-varying Atlantic Water circulation require further investigation. The major experiments for these studies can be subdivided on three categories:

- **general circulation of the Atlantic Water layer and causes of its variability;**
- **investigation the Atlantic Water inflow via Fram Strait in via St. Anna Trough (the Kara and Barents Seas), and**
- **High resolution structure of the AW boundary current**
- **model validations based on observations**

Coordinated experiments

***Ecosystem experiments:* K. Popova,** M. Steele, F. Dupont, D. Holland, T. Reddy, C. Hill, E. Hunke, et al.

Recognizing that marine ecosystem modeling is complex and that the ecosystems come in many forms, even in the Arctic Ocean environment, the AOMIP has decided to formulate a set on coordinated experiments to incorporate a relatively simple ecosystem modeling in their regional models of the Arctic Ocean. These experiments are important to our understanding of the changing Arctic marine environment. The arctic ecosystems are often highly complex and are affected by both cyclic and stochastic influences. Computer models, combined with suitable data-collection programs, can help in deepening our understanding of these systems and how they will react to various influences (from climatologic to human).

Coordinated experiments

Observations, state estimation, and adjoint methods: P. Heimbach, F. Kauker, D. Stott, G. Panteleev

The major goal for this theme is to discuss the role of observations for AOMIP, and the need of taking optimal advantage of them through rigorous estimation (data assimilation) methods. Depending on the application, very different requirements can be placed on the estimation/assimilation system which have to be recognized and respectively evaluated. Another problem is to identify the relevant data (both observational specifically organized for AOMIP model validation), and where and how to archive the data for better distribution among AOMIP collaborators and throughout the Arctic observational and modeling communities.

Distribution & archiving of observations and AOMIP model results:

Various data servers already exist (e.g. NSIDC for sea ice, Damocles, etc), and questions are, how to best harness existing servers, facilitate data gathering for modelers, harmonize data formats, and encourage (or enforce?) provision of error estimates and their correlations for each data set.

Coordinated experiments

Observations, state estimation, and adjoint methods: P. Heimbach, F. Kauker, D. Stott, G. Panteleev

(1) AOMIP is an ARCSS funded project within the NSF Office of Polar Programs, and archiving of metadata for the AOMIP project results would be through the NCAR ARCSS Data Archive, see: http://www.eol.ucar.edu/projects/arcss/

(2) The archiving of AOMIP model files – for setting up the model runs and also the output when desired – should be centralized, in order to facilitate data exchange during the experiments and for data stewardship when the project is completed. Metadata records in other archives should point to the data at the centralized archive.

(3) NCAR/EOL will work with AOMIP to investigate and pursue the higher level of support for its data management needs. see: http://www.eol.ucar.edu/

Requirements of Arctic Ocean Hindcast and Forecast Models

Wieslaw Maslowski
Naval Postgraduate School

Collaborators:
Andrew Roberts, Jaclyn Clement Kinney,
Timothy McGeehan, Rose Tseng,
Terry McNamara, John Whelan - NPS
Jaromir Jakacki, Robert Osinski - IOPAS
John Cassano, Matthew Higgins - CU
William Gutowski, Justin Glisan, Brandon Fisel - ISU
Dennis Lettenmaier, Chunmei Zhu - UW

BOEMRE Workshop on Arctic Modeling for OSRA, SAIC, McLean, VA, 29-31 March, 2011

OUTLINE

- Arctic Models @ NPS/DOE
- Modeling requirements
  - Hindcast
    - Sea ice
    - Ocean
    - Atmosphere
  - Prediction
- Summary

NPS Ocean and Sea Ice Models

1. Navy Polar Ice Prediction System (PIPS 3.0)

a. Regional adaptation of LANL/POP (V_1.4) for the pan-Arctic

- Grid resolution: 1/12° or ~9 km using rotated spherical coordinate system
- New IBCAO bathymetry - Model Grid: 1280x720x45
- New (UW/PSC) hydrographic climatology
- Freshwater sources from river runoff (Yukon, Mackenzie, and Russian rivers)
- Numerical tracers for Pacific Water, Atlantic Water, and river runoff
- Completed ~150-year Integration:
    - 48-year spinup
    - 4 (25-yr) ensembles of 1979-2003 interannual forcing

b. Sea ice model (based on Hibler (1979) and Zhang et al. (1998) :
- 2-layer thermodynamics (Semtner 1976):
- VP dynamics

c. HPC hardware:
- Cray X-MP, Y-MP, C90, T3D, T90, J90, T3E, SV1, NEC SX-6, X1
- SGI Origin 2000/3000
- IBM Power4/5

d. HPC resources: Several to couple wall clock days to complete 1 model year

NPS Ocean and Sea Ice Models

1. Pan-Arctic POPCICE-12 (using own simple flux coupler)
   a. Regional POP (V.2)
      - Grid resolution: 1/12^{o} or ~9 km in rotated spherical coordinate
      - Grid size:1280x720x45
      - initial fields improved upon those from PIPS3
      - restarted from PIPS3 48-yr spinup
      - completed ~100 year Integration of sensitivity runs:

   b. Regional LANL/CICE (V.3.4):
      - energy-conserving thermodynamics with:
        4 ice categories, snow layer, nonlinear T, S profiles
      - EVP dynamics (Hunke and Dukowicz, 1997)
      - 2-D remapping for horizontal ice transport
      - 1-D remapping for thickness distribution
2. Pan-Arctic POPCICE-48 (using own simple flux coupler)
   a. Regional POP (V.2)
      - Grid resolution: 1/48^{o} or 2.36 km using rotated spherical coordinate system
      - Grid size: 5120x2880x48
      - completed 5-year spinup (further runs pending 9-km sensitivity studies)

   b. Regional LANL/CICE (V.3.4) – same as 9-km version

Regional Arctic Climate Model (RACM)

- **Atmosphere - Polar WRF** (gridcell ≤50km)
- **Land Hydrology – VIC** (same as WRF)
- **Ocean - LANL/POP** (gridcell ≤10km)
- **Sea Ice - LANL/CICE** (same as POP)
- **Flux Coupler – NCAR CPL7**
- **NCAR CCSM4 framework used for developing RACM**

Components with higher resolution are evaluated and will be implemented subject to availability of computer resources

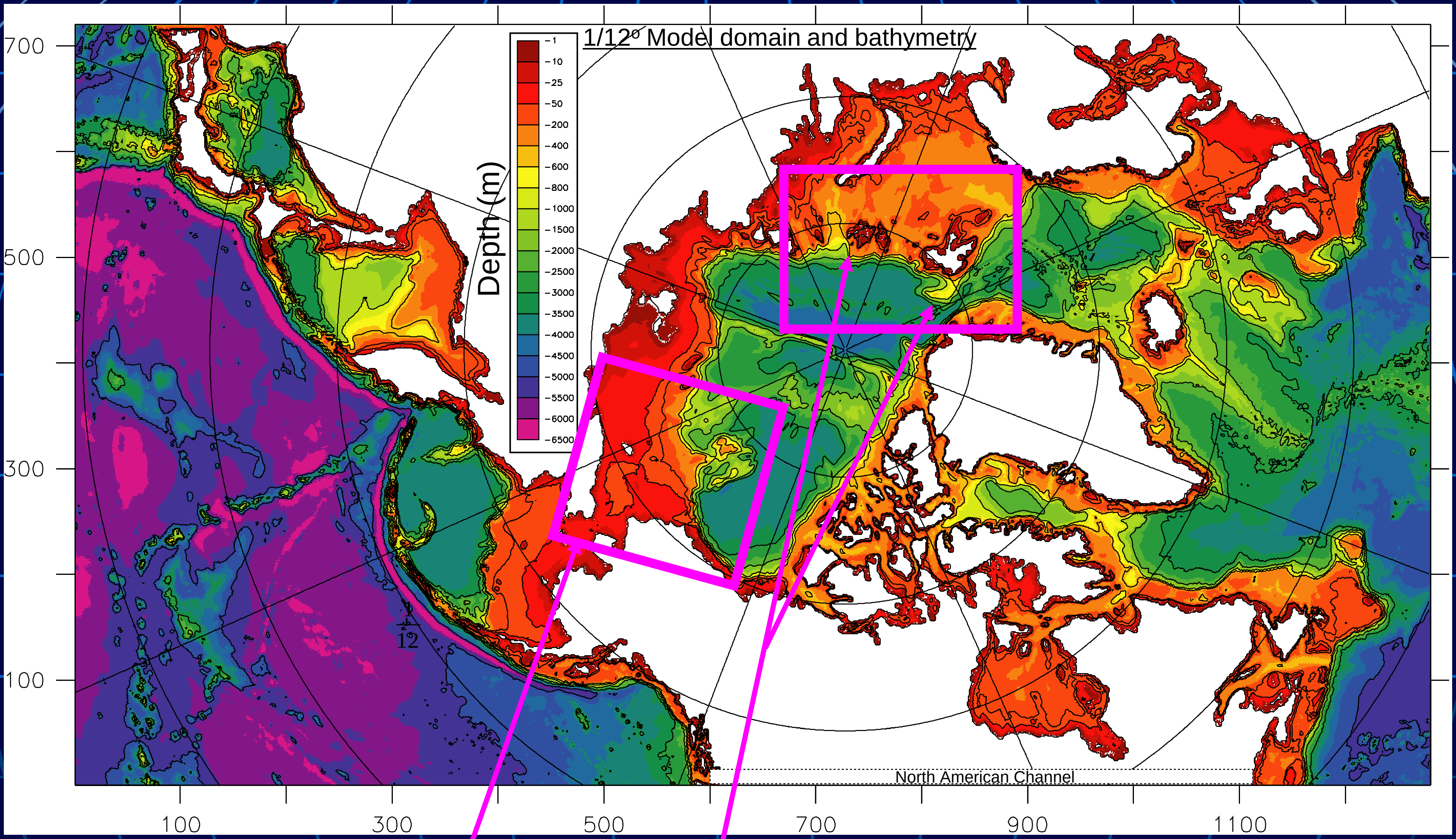
Collaborators:

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

Regional Arctic System Model (RASM)

- **All RACM model components +**
- **Dynamic Vegetation – VIC(4.1.1) + CLM(4.0)** (same as WRF)
- **Dynamic Ice Sheet – Glimmer-CISM plus** (gridcell ≤5km)
- **Glacier and Ice Caps (GIC)**
- **Plug-compatible approach (Kalney et al., 1989)**

- Participants:
- Wieslaw Maslowski (PI) - Naval Postgraduate School
- Andrew Roberts (co-PI) - Naval Postgraduate School
- John Cassano, Matthew Higgins (co-PI) - University of Colorado
- William Gutowski (co-PI) - Iowa State University
- Dennis Lettenmeier (co-PI) - University of Washington
- William Lipscomb (co-PI) - Los Alamos National Laboratory
- Slawek Tulaczyk (co-PI) - University of California Santa Cruz
- Xubin Zeng (co-PI) - University of Arizona
- William Robertson (co-PI) - University of Texas El Paso



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

Main uncertainties of importance to global climate

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

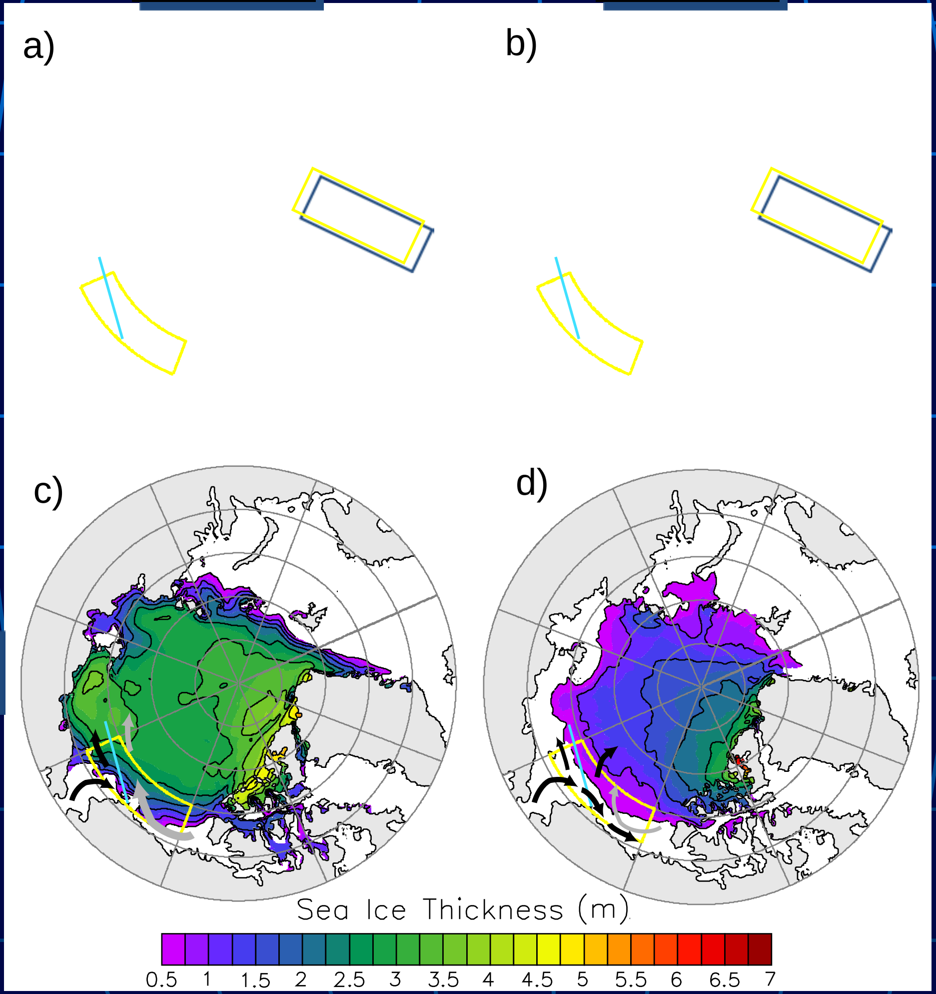
Sea Ice / Ocean modeling in RASM

Observed Arctic sea ice extent (a,b) modeled sea ice thickness (c,d) during September 1979 (a,c) and 2002 (b,c)

09/79 **09/02**

SSM/I – 2D

MODEL - 3D

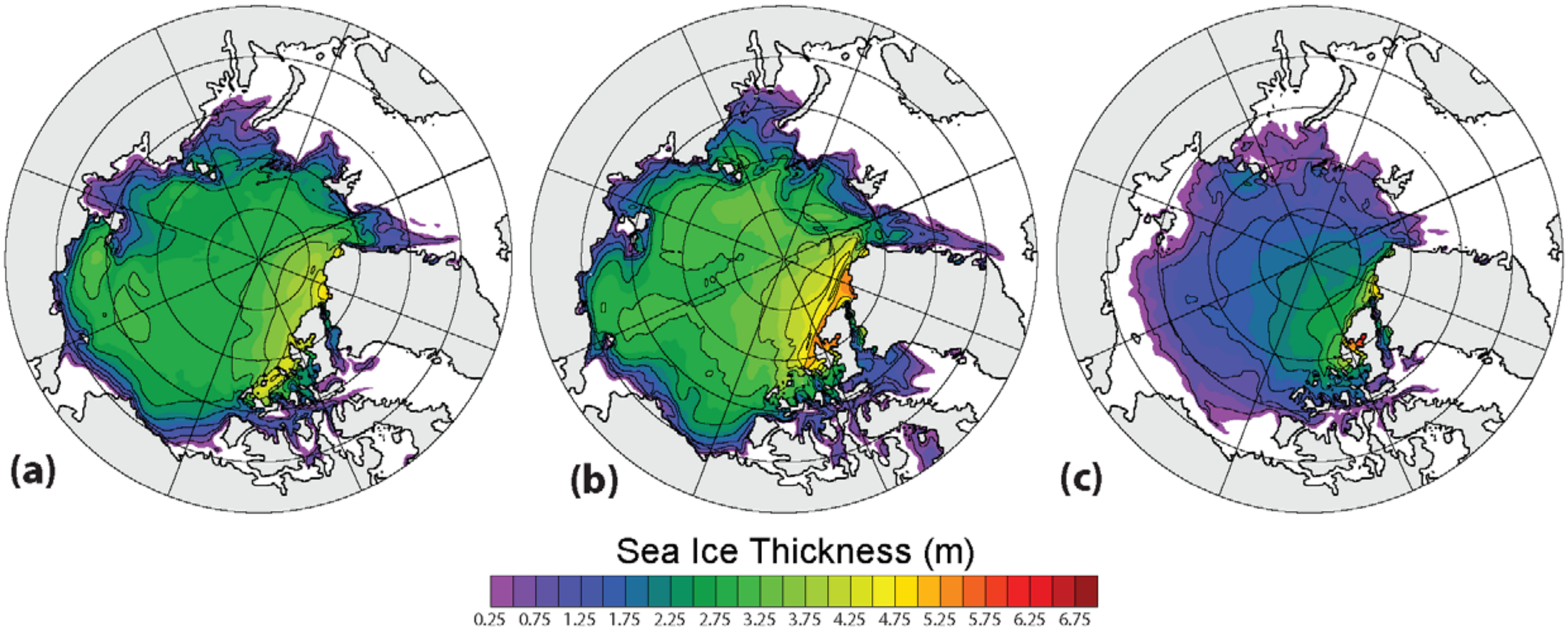


Reduction of modeled ice thickness (up to 1.5-2.0 m or ~35%) is roughly twice the decrease in observed sea ice extent (17-20%; top)

Note that largest changes are downstream of Pacific / Atlantic water inflow into the Arctic Ocean.

Decadal sea ice thickness variability

(Maslowski et al., 2007)



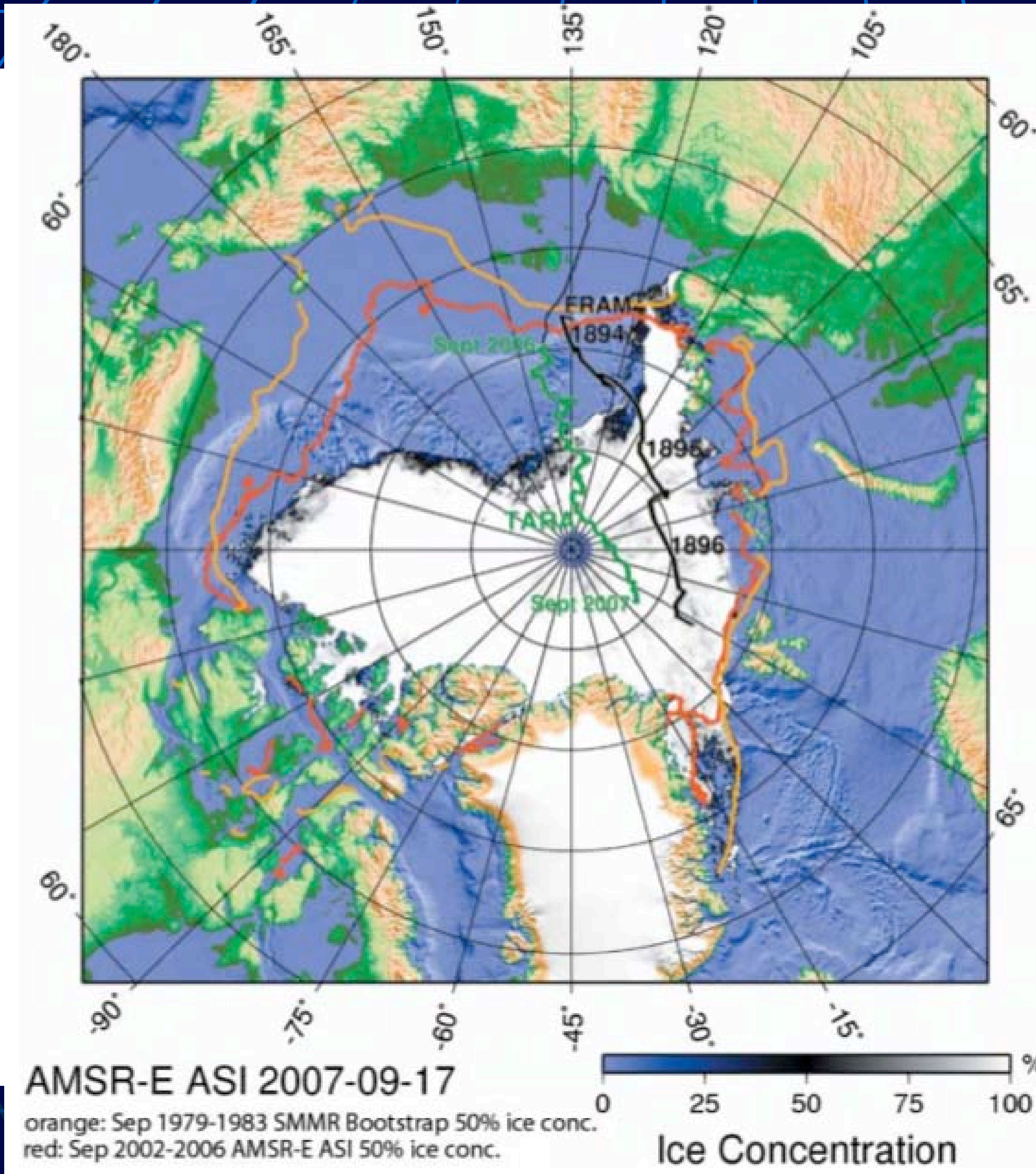
Modeled Arctic sea ice thickness distribution [m] in September a) 1982, b) 1992, c) 2002.
The same color scale in all panels emphasizes dramatic reduction of ice thickness in the 2000s

Shift from the mode thickness of 2.5-3.5 m in the 1980s to mid-1990s to 1.5-2.5 in the 2000s

Result: ~33% reduction of ice thickness in the 2000s!

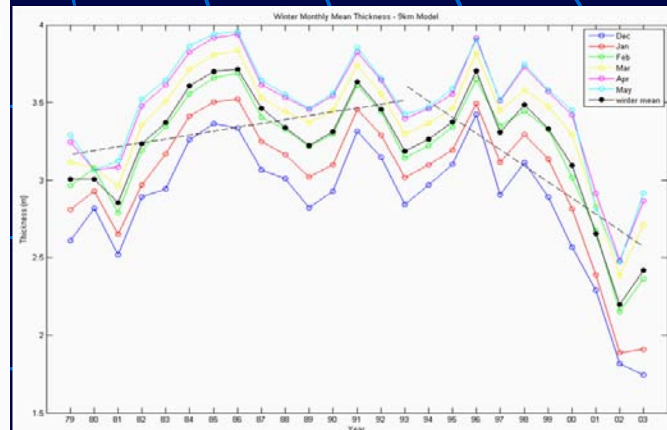
Tara (09/06-09/07) vs Fram (1894-1896) Drift

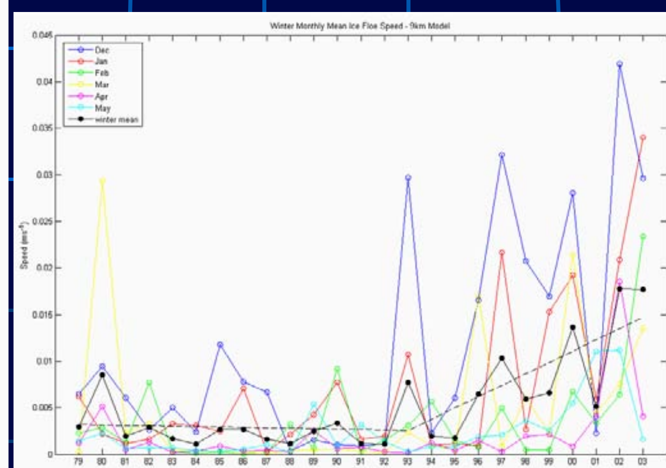
Fig. 1. The drift track of Ice Station Tara from September 2006 to September 2007 and the drift track of the Fram (1894–1896) are represented. The bottom topography is shown together with sea ice summer minimum extent in 2005 and 2007.



Gascard et al., Eos, Vol. 89, No. 3, 15 January 2008

Tara drift 2-3 times faster compared to Fram drift.

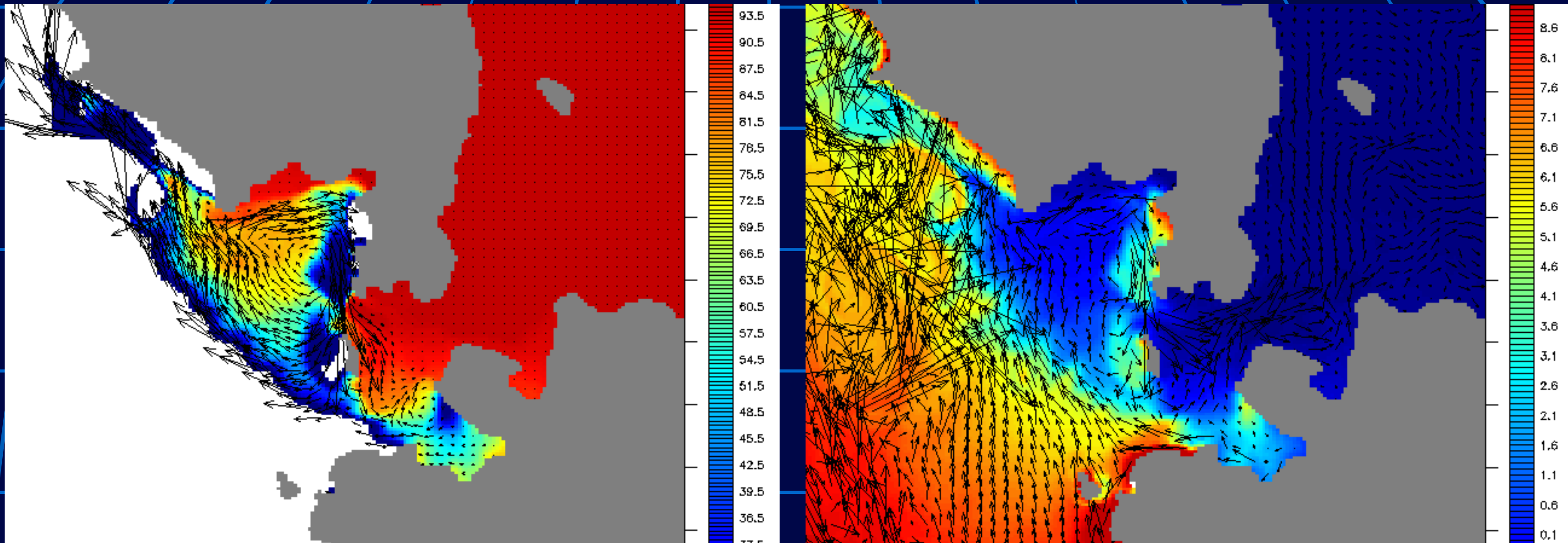




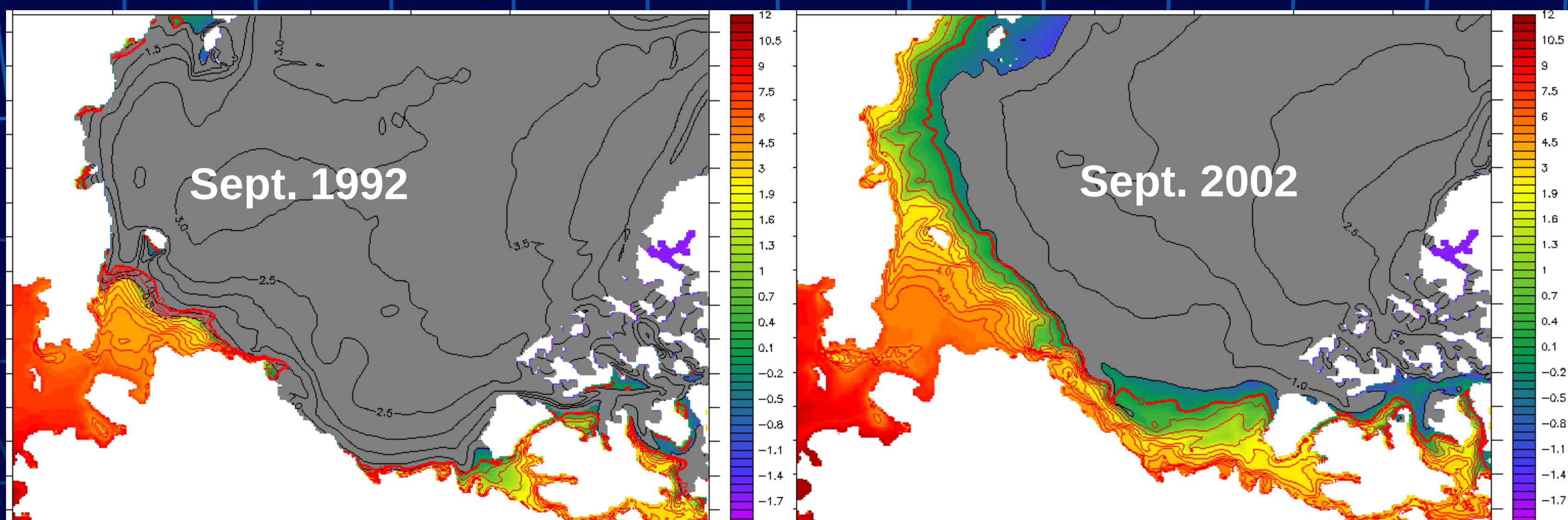
Thinner ice moves faster (e.g. Tara Exp.) and deforms easier

Bering Sea Marginal Ice Zone - 05/79

Ice Concentration (%) & Velocity (m/s) (left) and SST (0-5 m; °C) & Velocity (cm/s) (right)

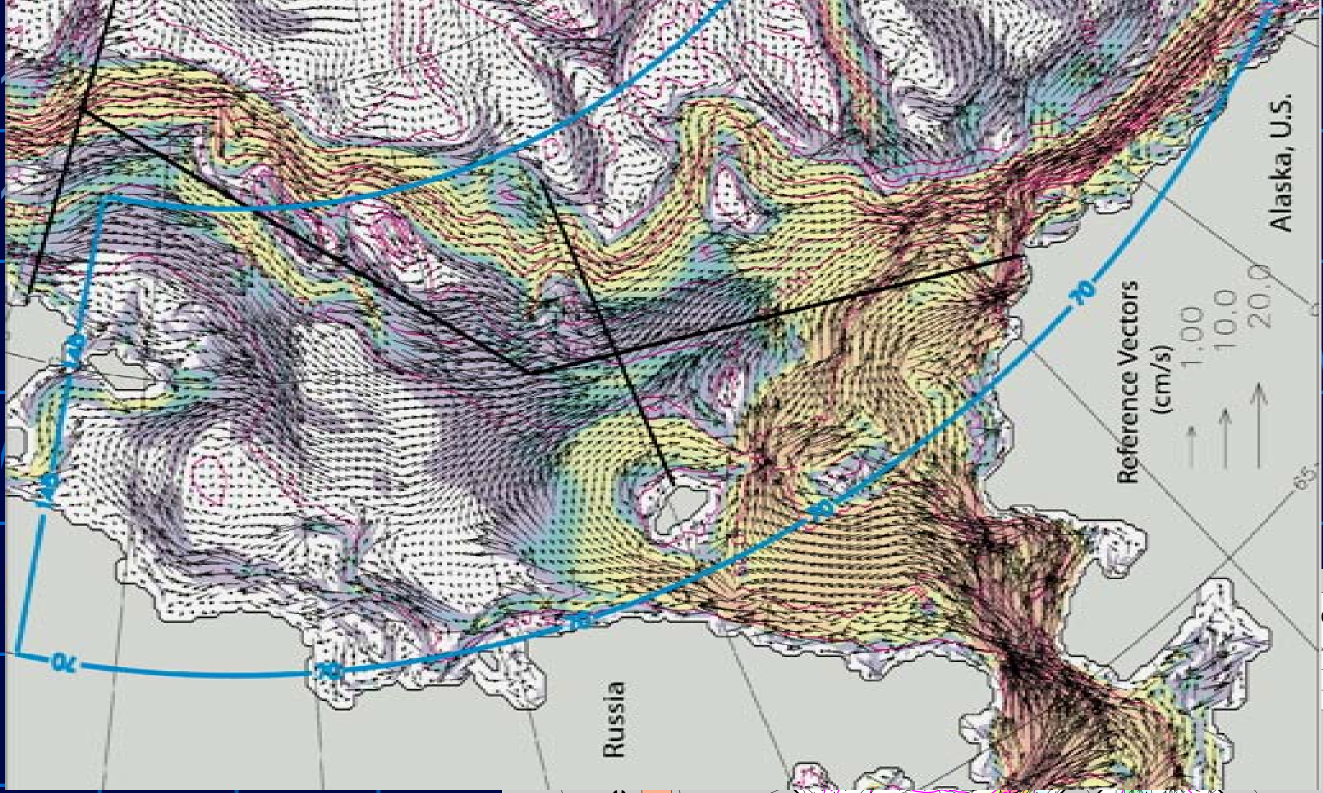


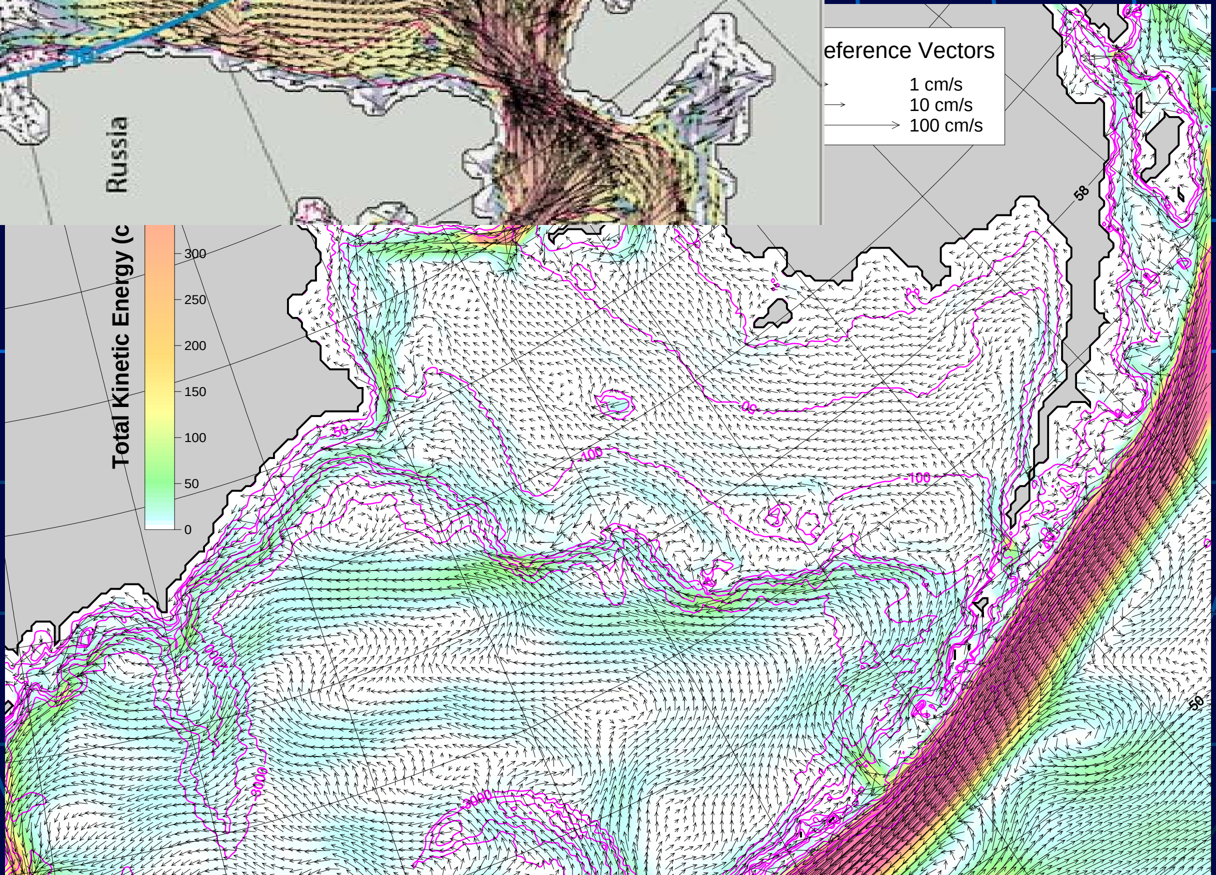
Interannual Variability of SST and Sea Ice Thickness (gray) Interaction



Ice edge region strongly controlled by the surface ocean temperature and

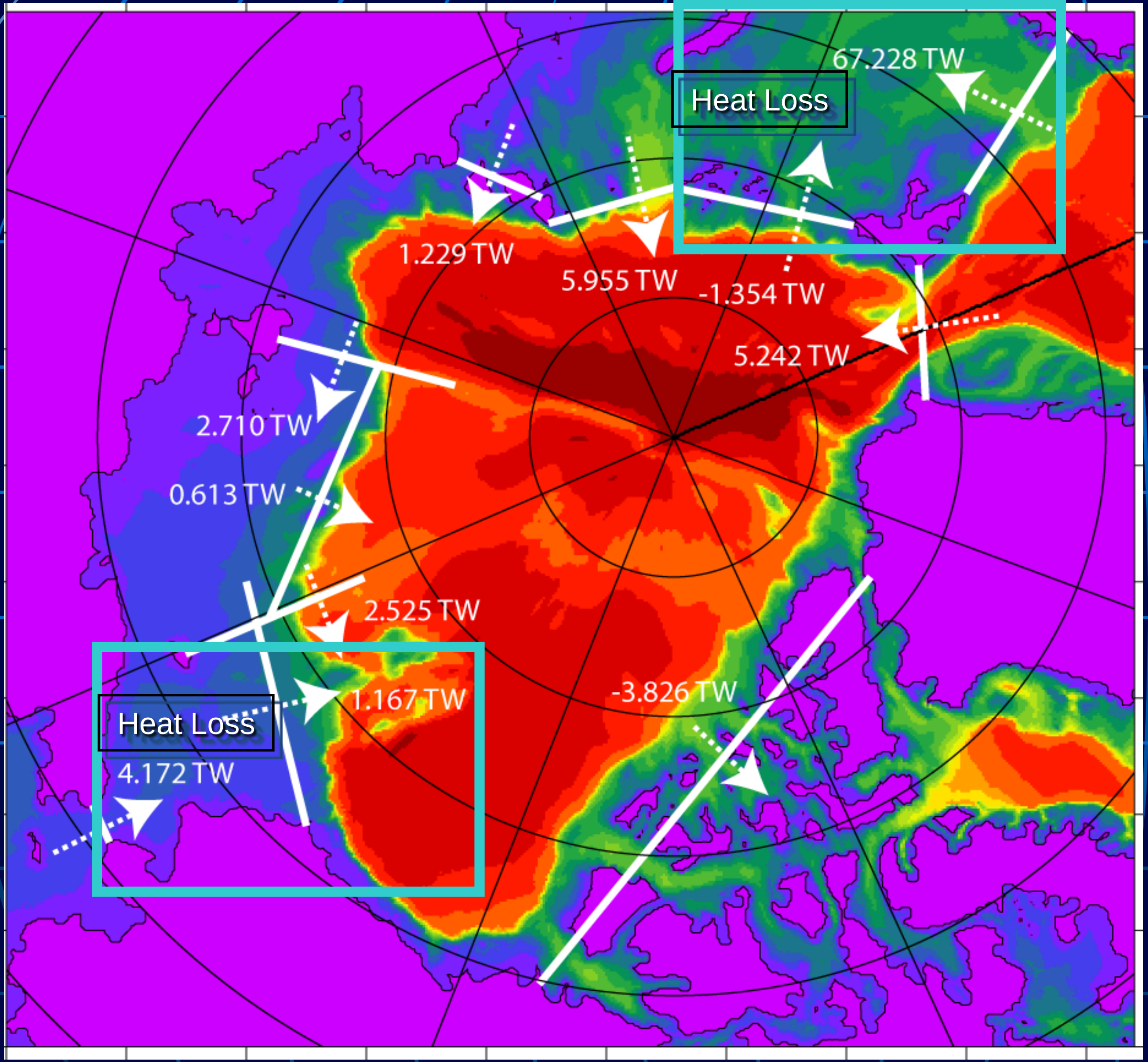
Mean modeled upper ocean circulation upstream, at, downstream of the Bering Strait





Flow through Bering Strait influences water masses, sea ice, ecosystem and climate of the western Arctic Ocean

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



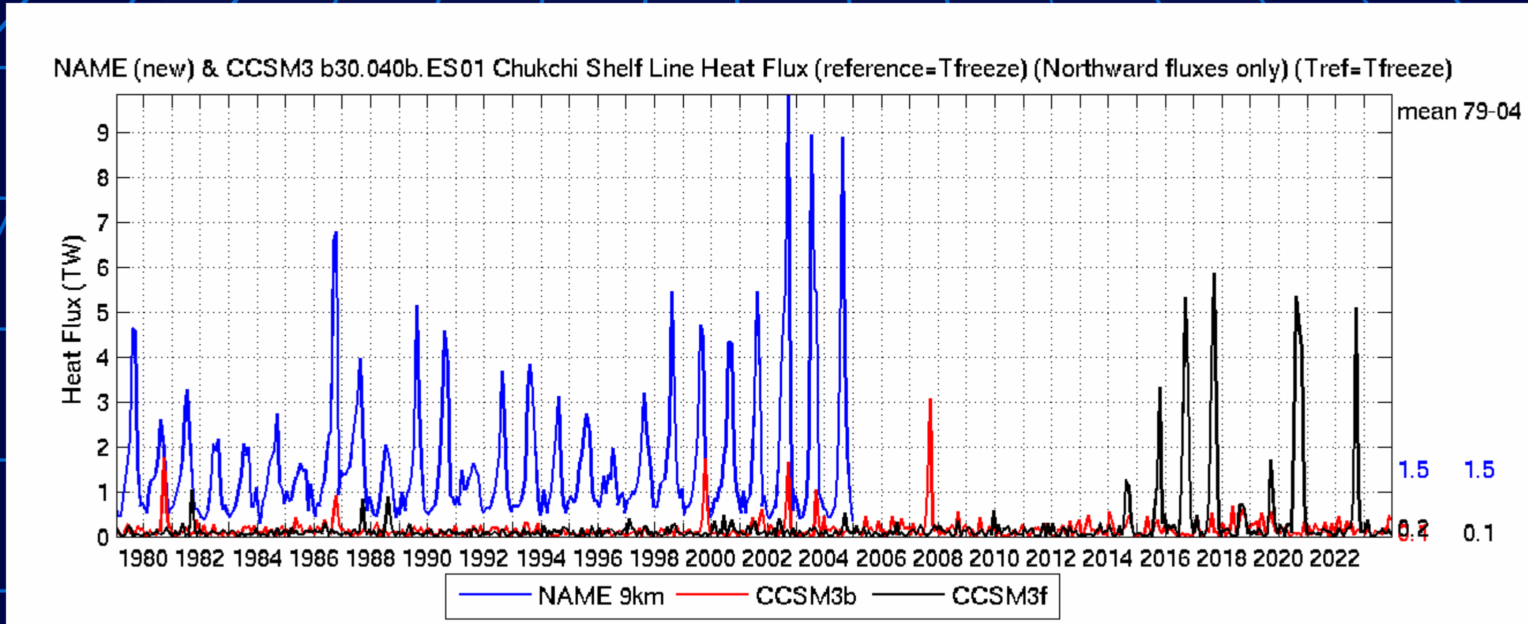
Modeling Challenges: Inflow of Pacific / Atlantic Water into the Arctic Ocean

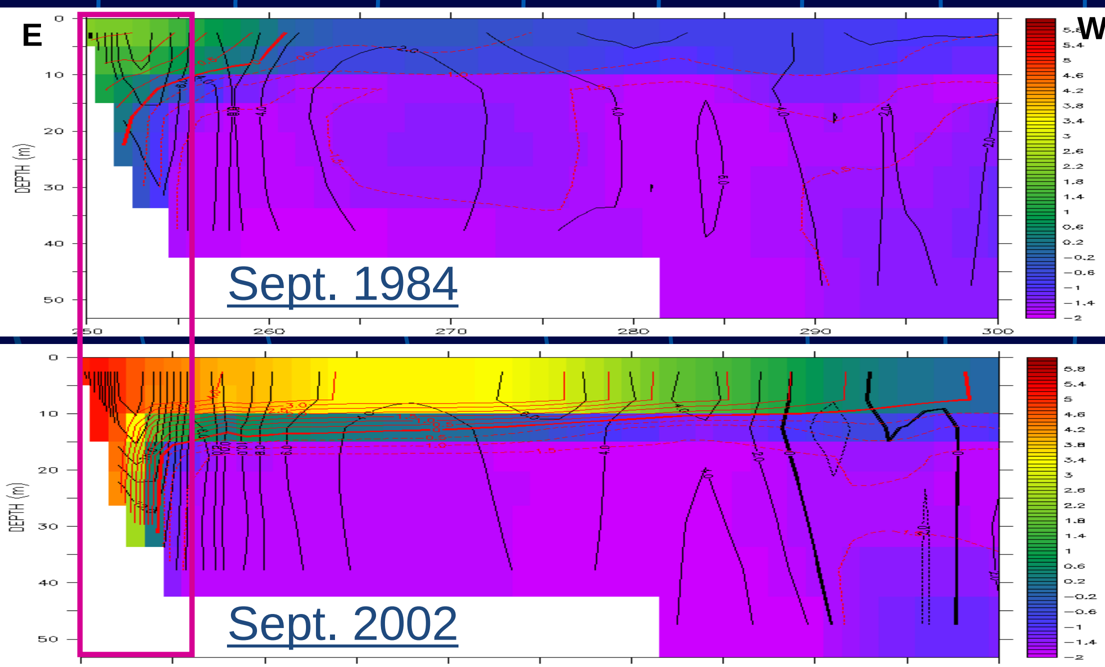
- Pacific Water entering via narrow (~60mi) Bering Strait
- outflow through Fram Strait vs. Atlantic Water inflow (FSBW)
- Atlantic (BSBW) and Pacific Water each losses majority of heat to the atmosphere before entering Arctic Basin

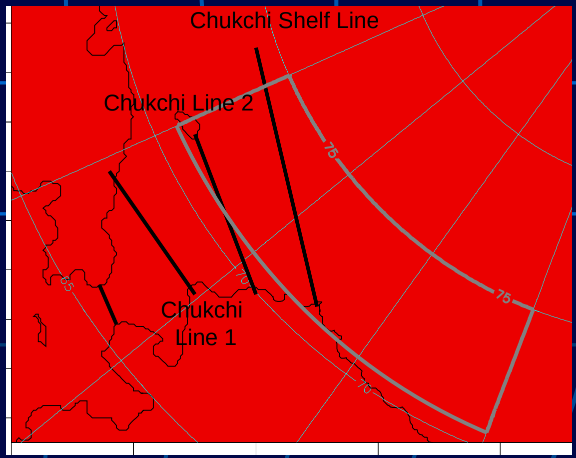
Arctic ocean-ice-atm feedbacks – not represented realistically in climate models

High resolution is one of the top requirements for advanced modeling of Arctic climate

Modeled Oceanic heat flux exiting the Chukchi Shelf

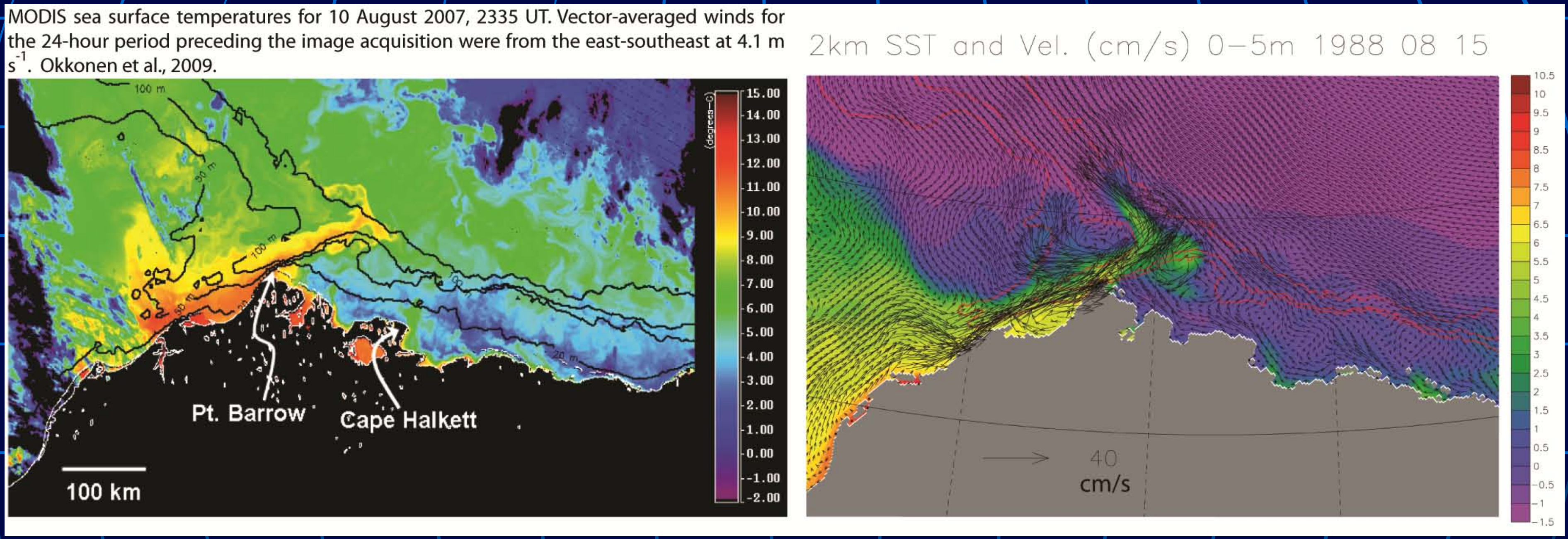






Heat Flux via Alaska Coastal Current accounts for ~67% of the Total Heat Flux across Chukchi Shelf Line

Ice-albedo versus ocean circulation effects



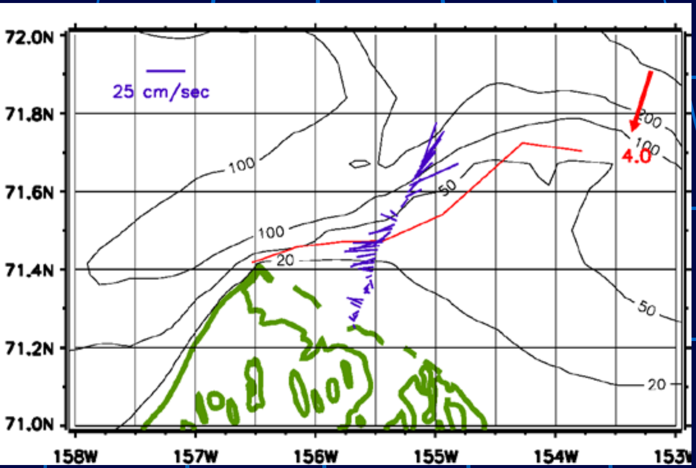
MODIS SST – 08/10/2007, 2335UT

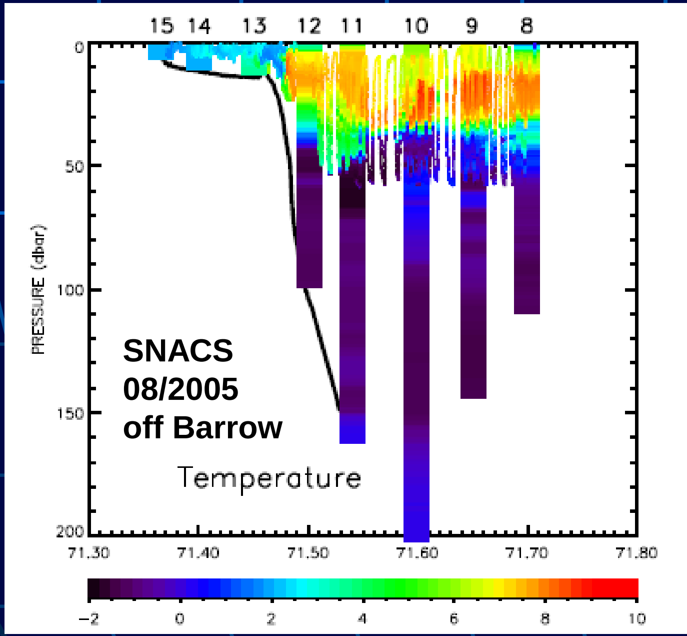
Modeled SST and Velocity – 08/15/1988

- Surface warming due to ice-albedo up to ~7^{o}C
-ACC carries water up to 13^{o}C and it extends below the surface
- At resolution of ~2 km models can capture details of ocean circulation, eddy generation and heat distribution

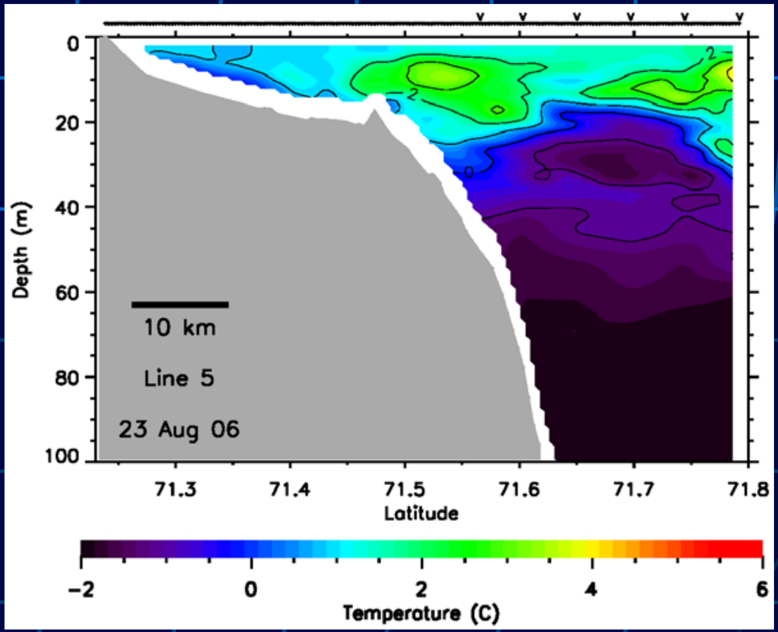
Oceanic advection and eddies transports heat from the Chukchi Shelf towards and under the ice cover

Mesoscale eddies distribute heat from the shelves, slopes and under the sea ice





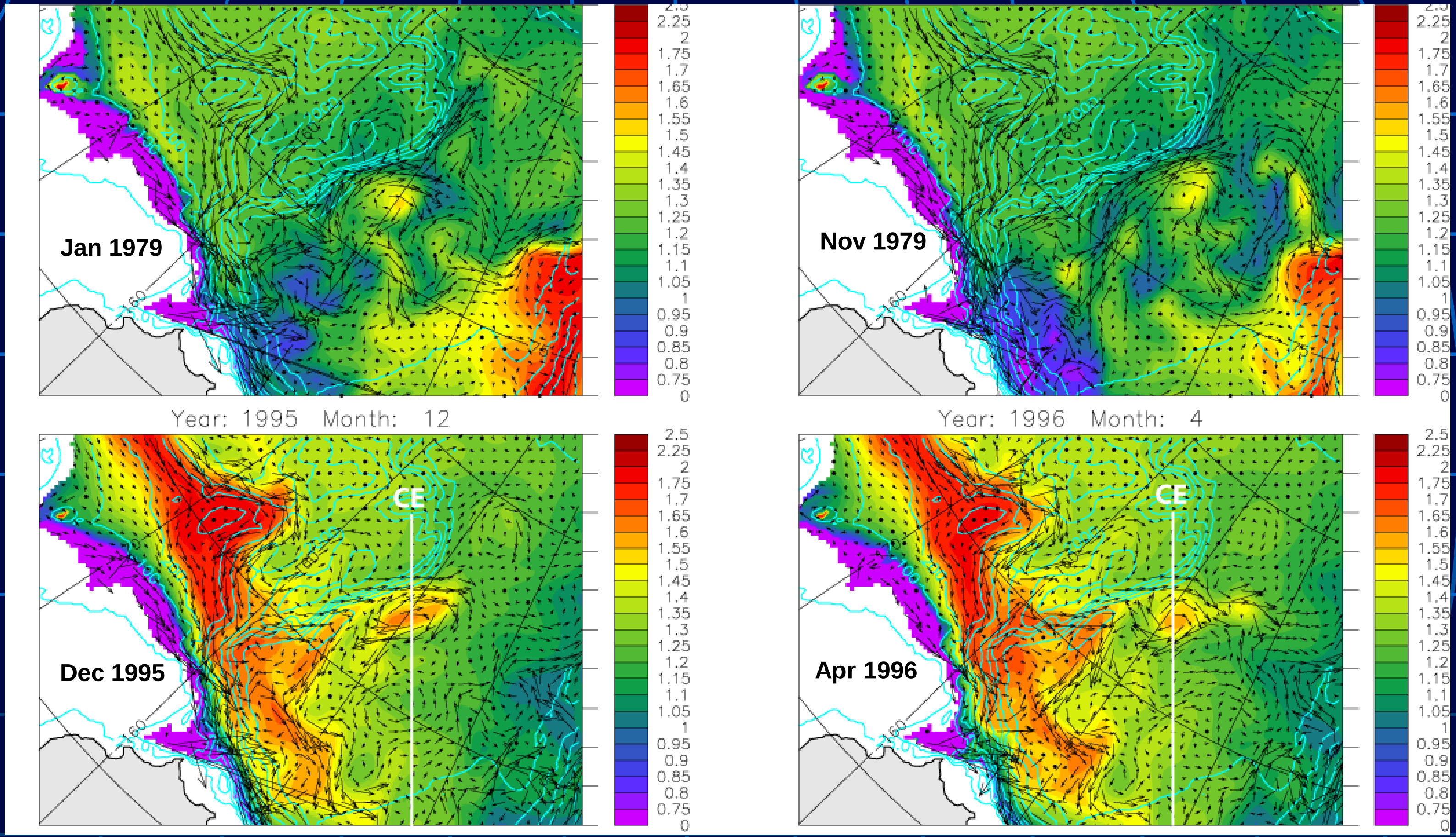
(Okkonen et al., JGR 2009)



(courtesy of S. Okkonen)

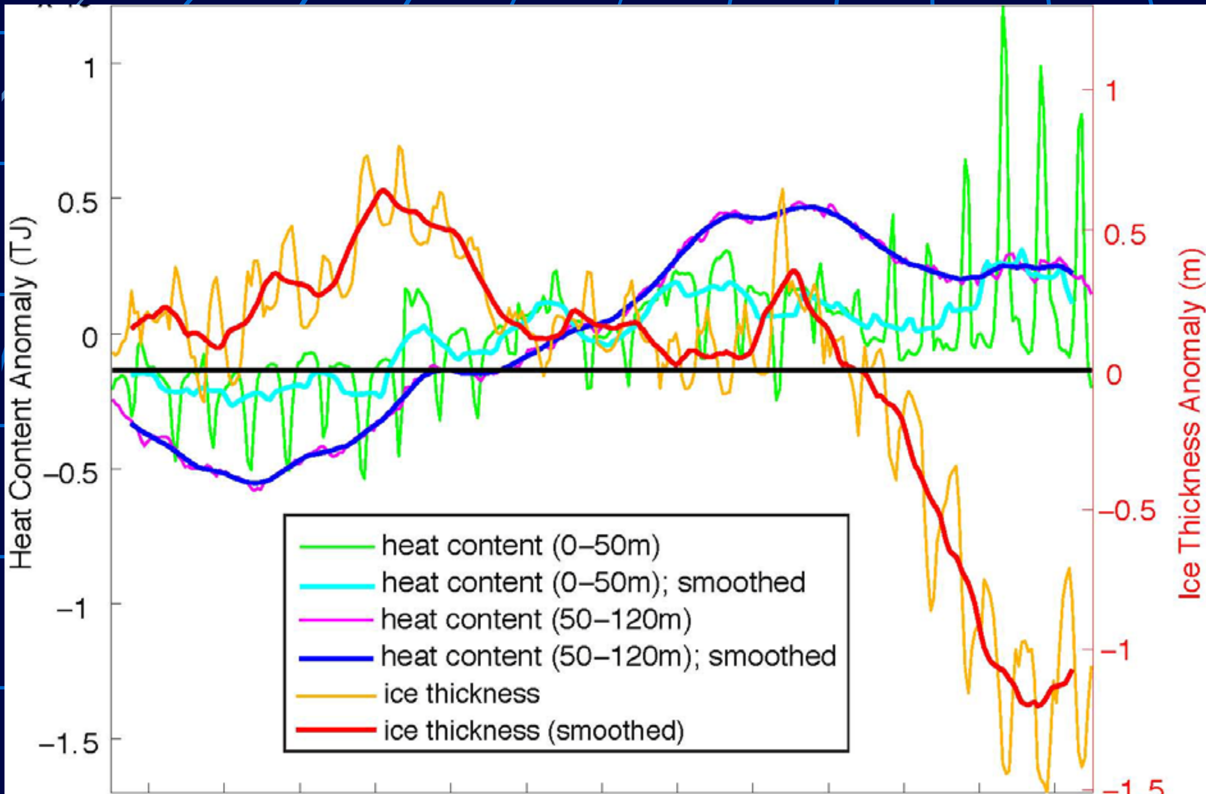
Increasing impact of eddy-driven oceanic heat input into the western Arctic

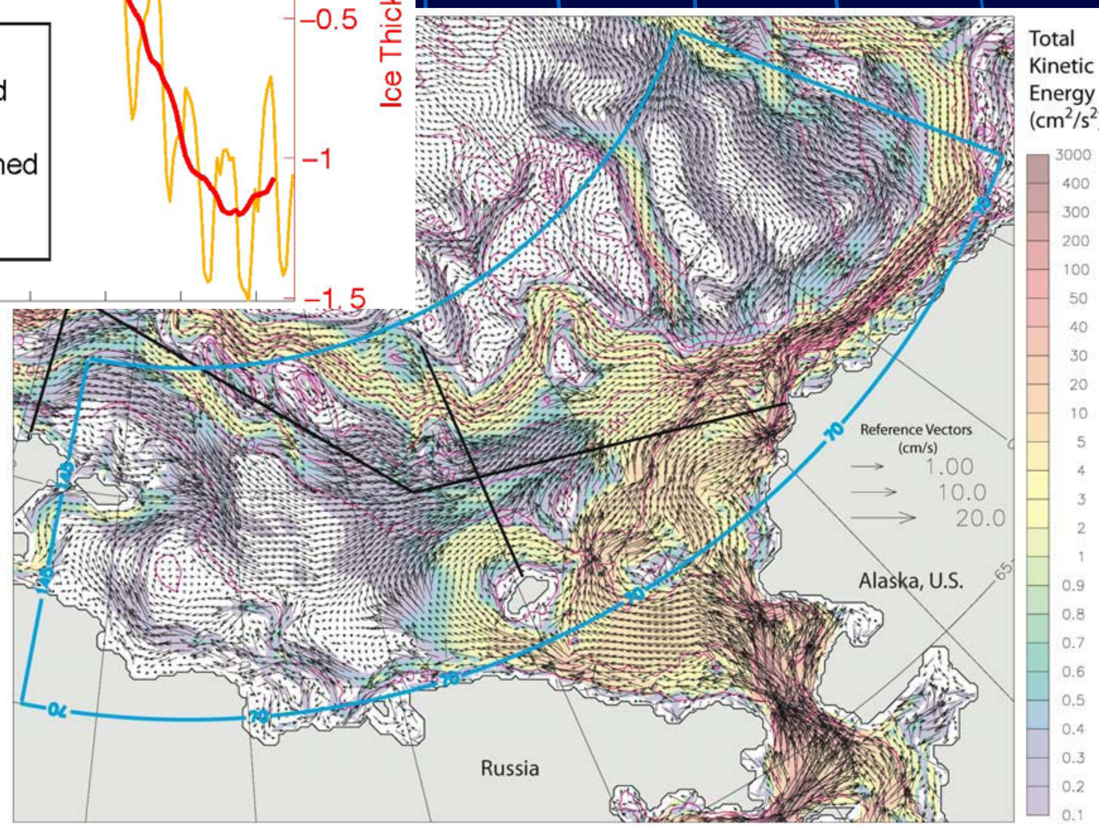
Depth-averaged (65-120m) temperature above freezing and velocity



Modeled Upper Ocean Heat Content and Ice Thickness Anomalies

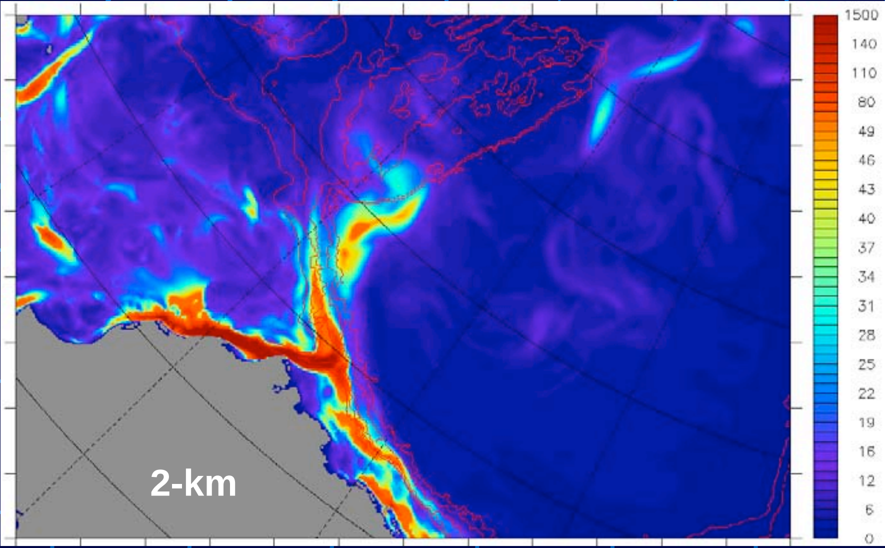
(Mean Annual Cycle Removed)

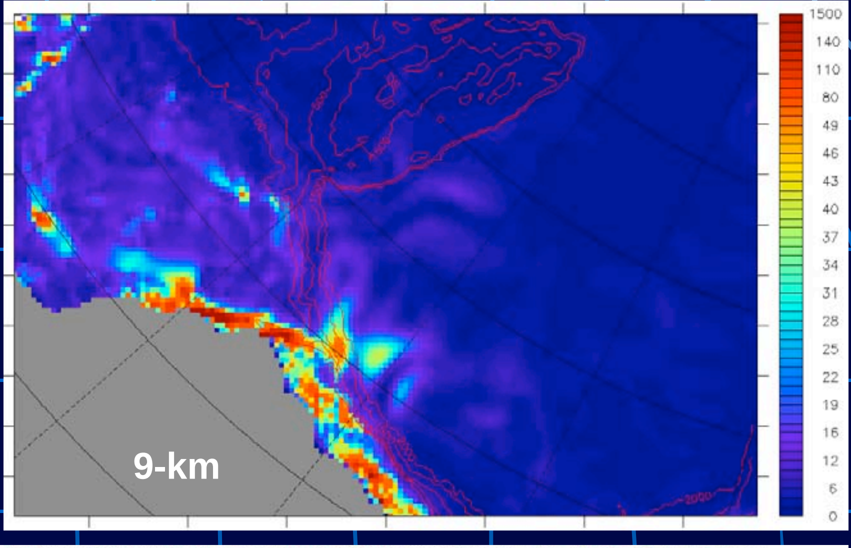


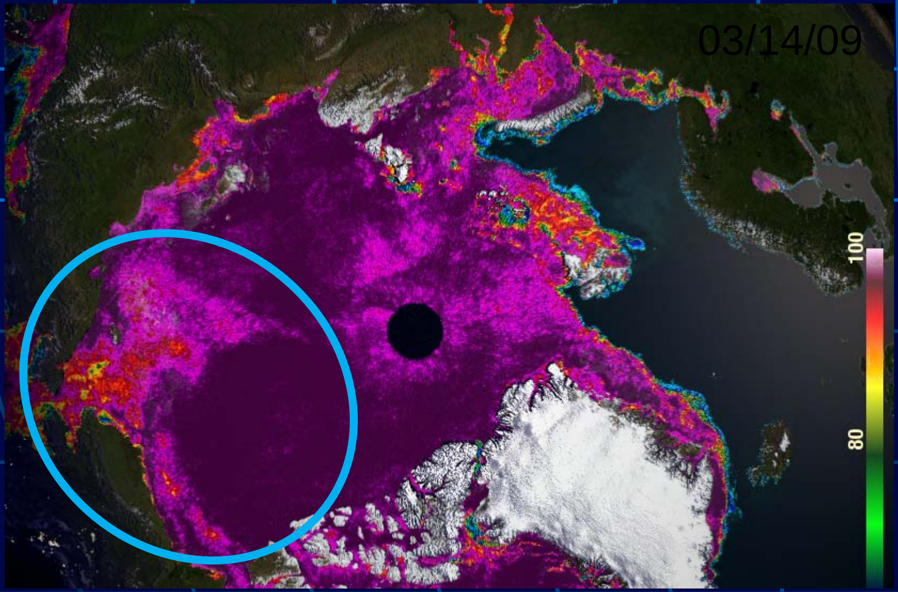


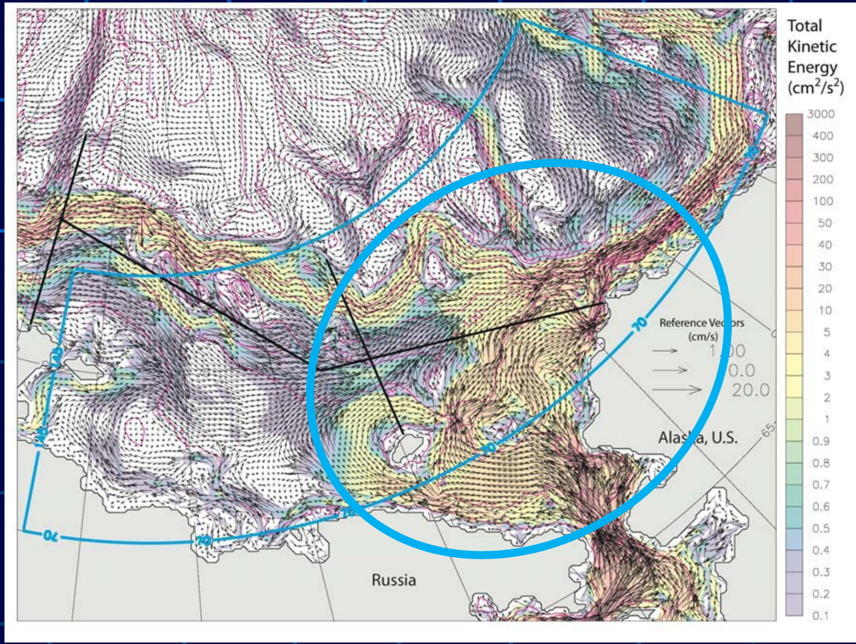
Heat content accumulated in the sub-surface ocean since mid-1990s can explain over 60% of total sea ice thickness change

Eddy activities over the Northwind Ridge : Summer (JAS) mean EKE in the upper 110m from 1/48o (left) and 1/12o (right) model



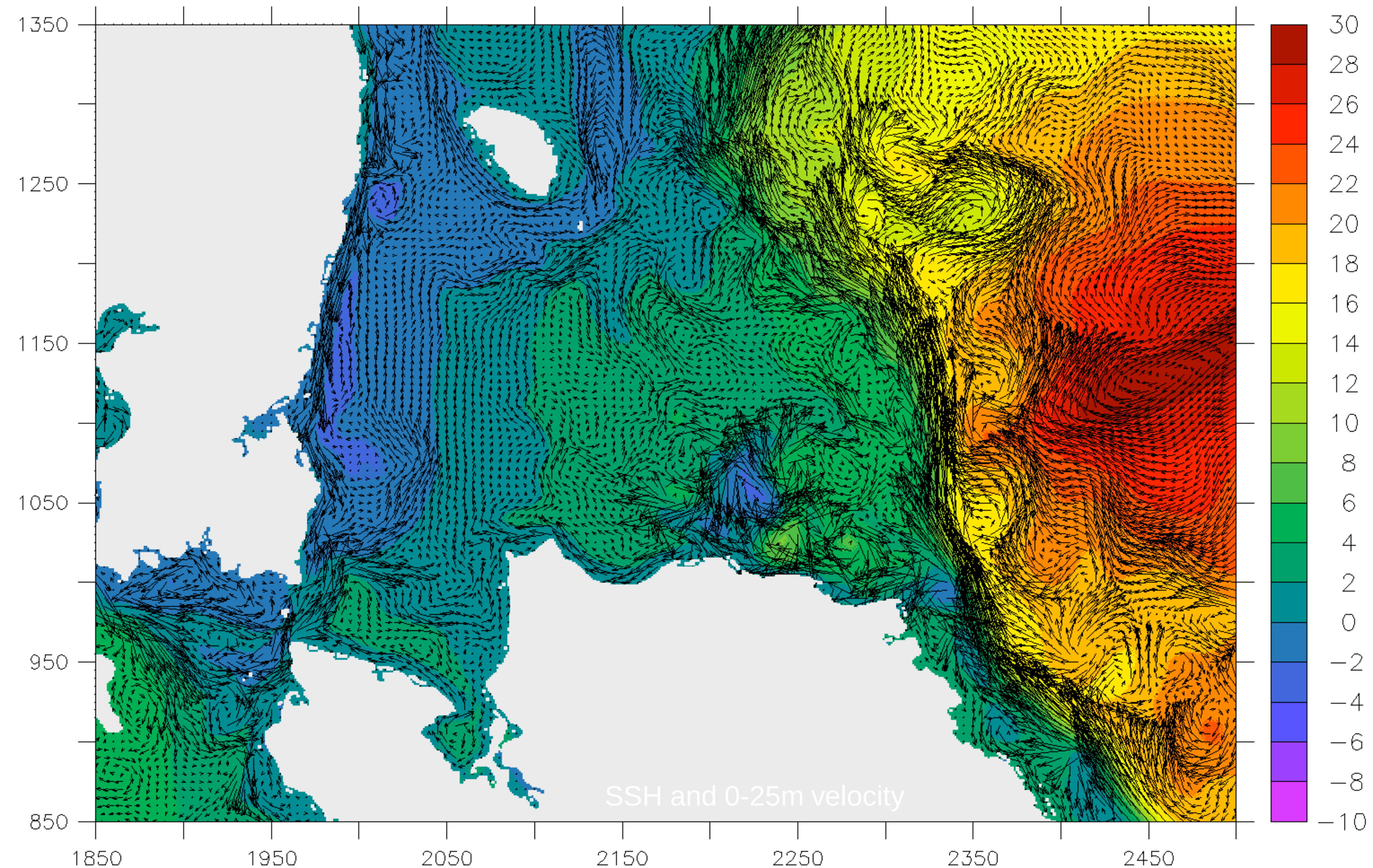






Oceanic impact on sea ice in the western Arctic …… continues!

1/48° (2.36 km) pan-Arctic POP model configuration



Many and more energetic eddies with radius >15 km resolved

Regional Arctic Climate System Model (RACM) – An Overview

A 4-year (2007-2011) DOE / ESM project

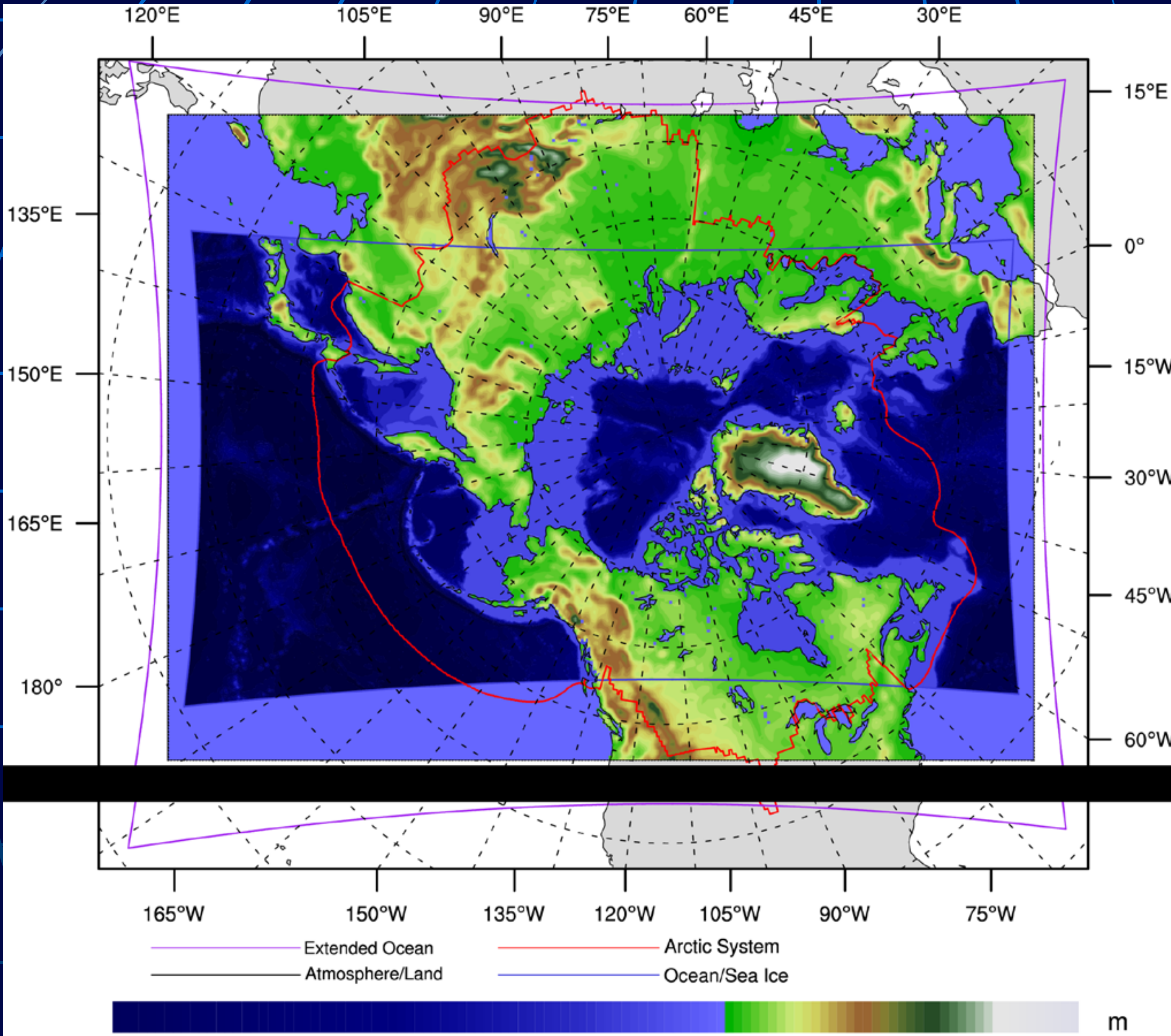
Participants:

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

Gabriele Jost (HPCMO), Tony Craig (NCAR), Jaromir Jakacki, Robert Osinski (IOPAN), Mark Seefeldt (CU), Chenmei Zhu (UW), Justin Glisan, Brandon Fisel (ISU), Jaclyn Kinney (NPS)

Greg Newby, Andrew Roberts, Juanxiang He, Anton Kulchitsky - Arctic Region Supercomputing Center / International Arctic Research Center

RASM Domains for Coupling and Topography



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)

RASM pan-Arctic model domain. WRF and VIC model domains include the entire colored region. POP and CICE domains are bound by the inner blue rectangle. Shading indicates model topobathymetry. The Arctic System domain (red line) is defined in Roberts et al. (2010).

Why Regional Arctic Climate System Model?

- Large errors in global climate system model simulations of the Arctic climate system
- Missing air-sea-ice feedbacks in regional stand-alone models
- Atmospheric conditions not realistically represented

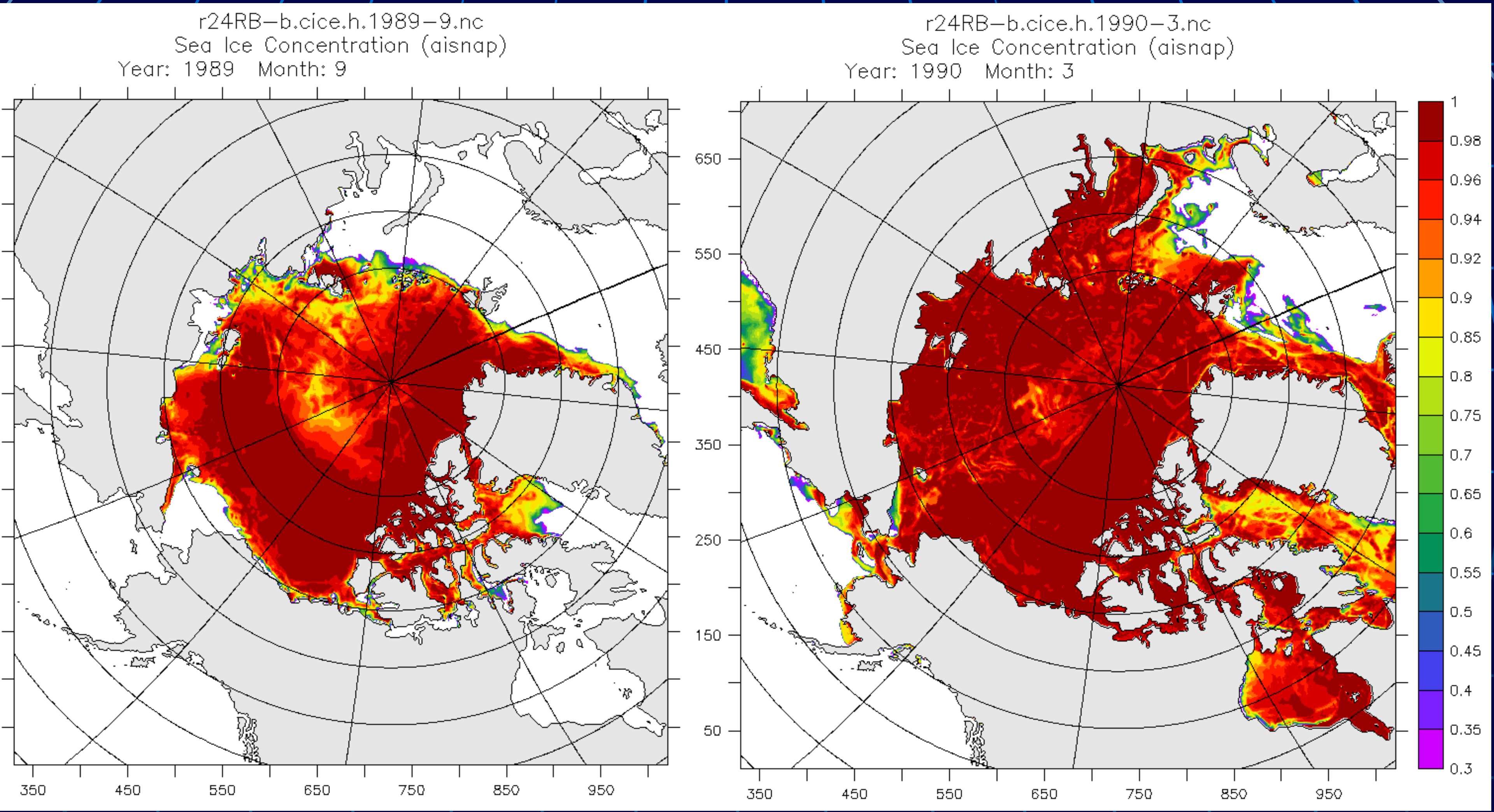
- Observed rapid changes in Arctic climate system
  – Sea ice decline
  – Greenland ice sheet
  – Temperature
- Arctic change has global consequences
  – can alter the global energy balance and thermohaline circulation

(A Science Plan for Arctic System Modeling – Roberts et al., 2010)

Rationale for developing a Regional Arctic Climate system Model (RACM)

1. **Facilitate focused regional studies of the Arctic climate**
2. **Resolve critical details of land elevation, coastline and ocean bottom bathymetry**
3. **Improve representation of local physical processes & feedbacks (e.g. forcing & deformation of sea ice)**
4. **Minimize uncertainties and improve predictions of climate change in the pan-Arctic region**
5. Develop a state-of-the-art Regional Arctic Climate Model (RACM)
6. High-resolution model output for regional assessment and policy making

RACM: Sea Ice Concentration



September 1989

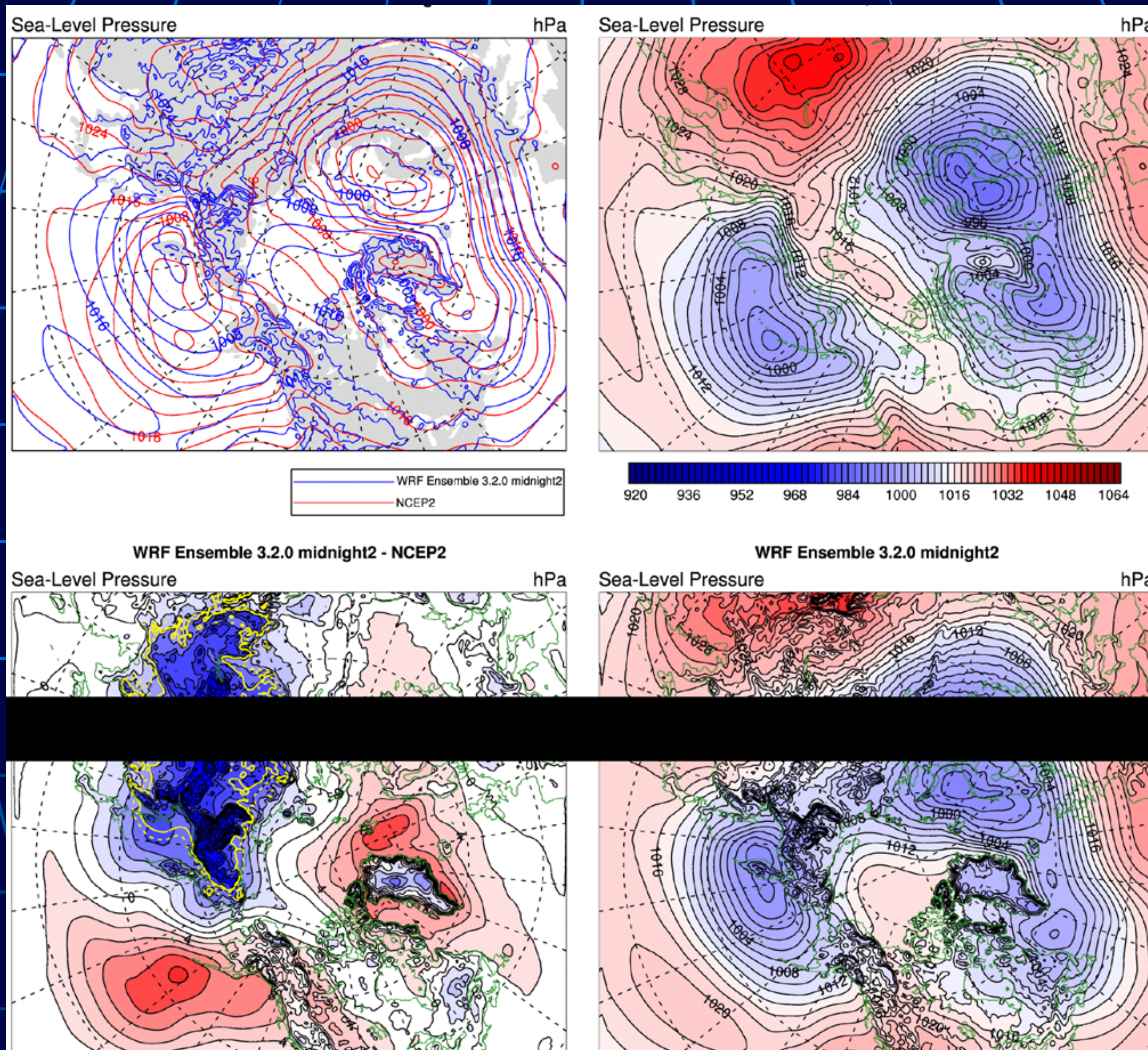
March 1990

January, 2007 SLP

Stand-alone WRF 3.2.0, “best case” with default 50 mb top

Overlay: WRF (blue), NCEP2 (red)

NCEP2



Difference

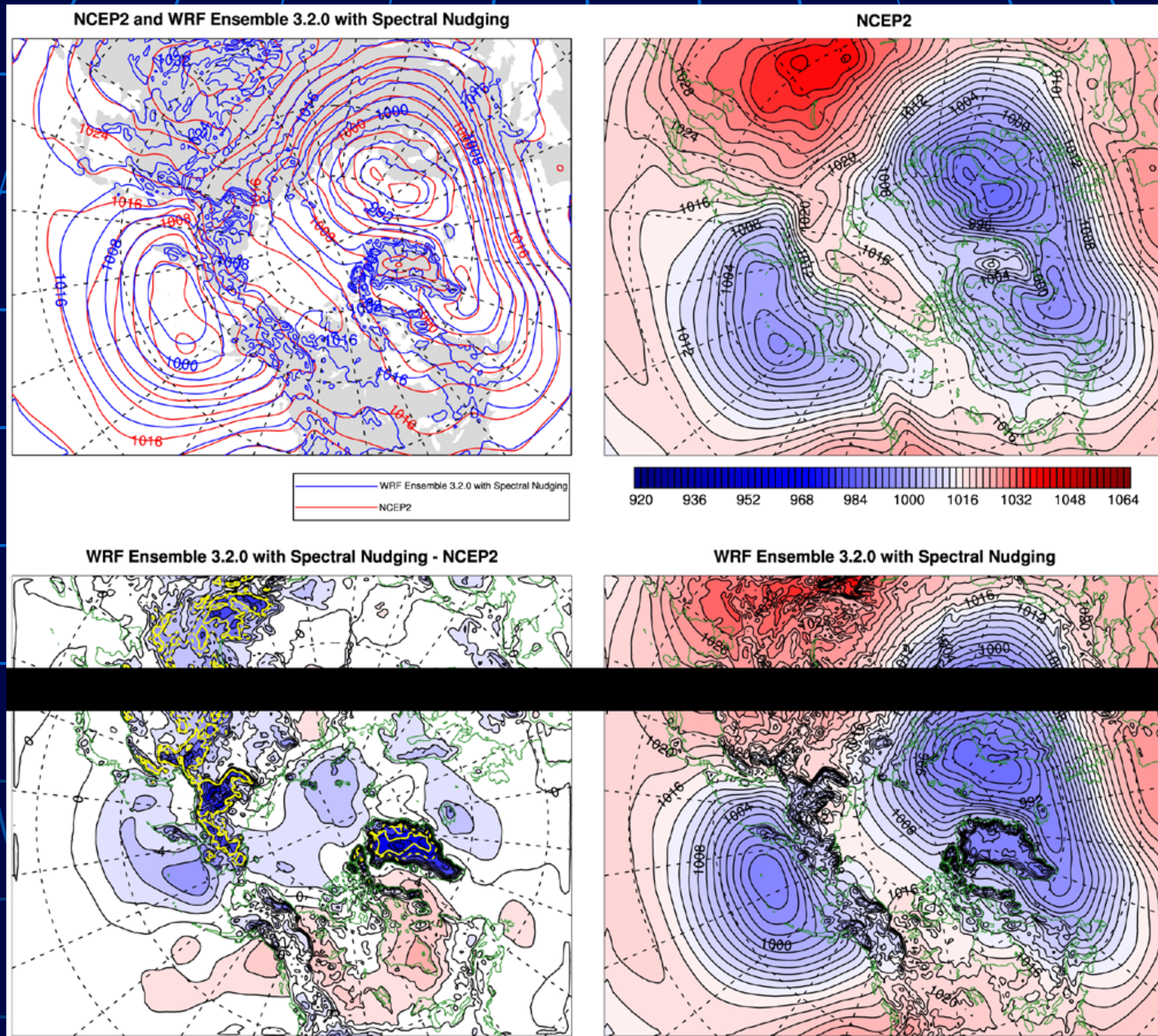
WRF

January, 2007 SLP

Stand-alone WRF 3.2.0, “best case”, default 50 mb top, spectral nudging

Overlay: WRF (blue), NCEP2 (red)

NCEP2



Difference

WRF

January, 2007 SLP

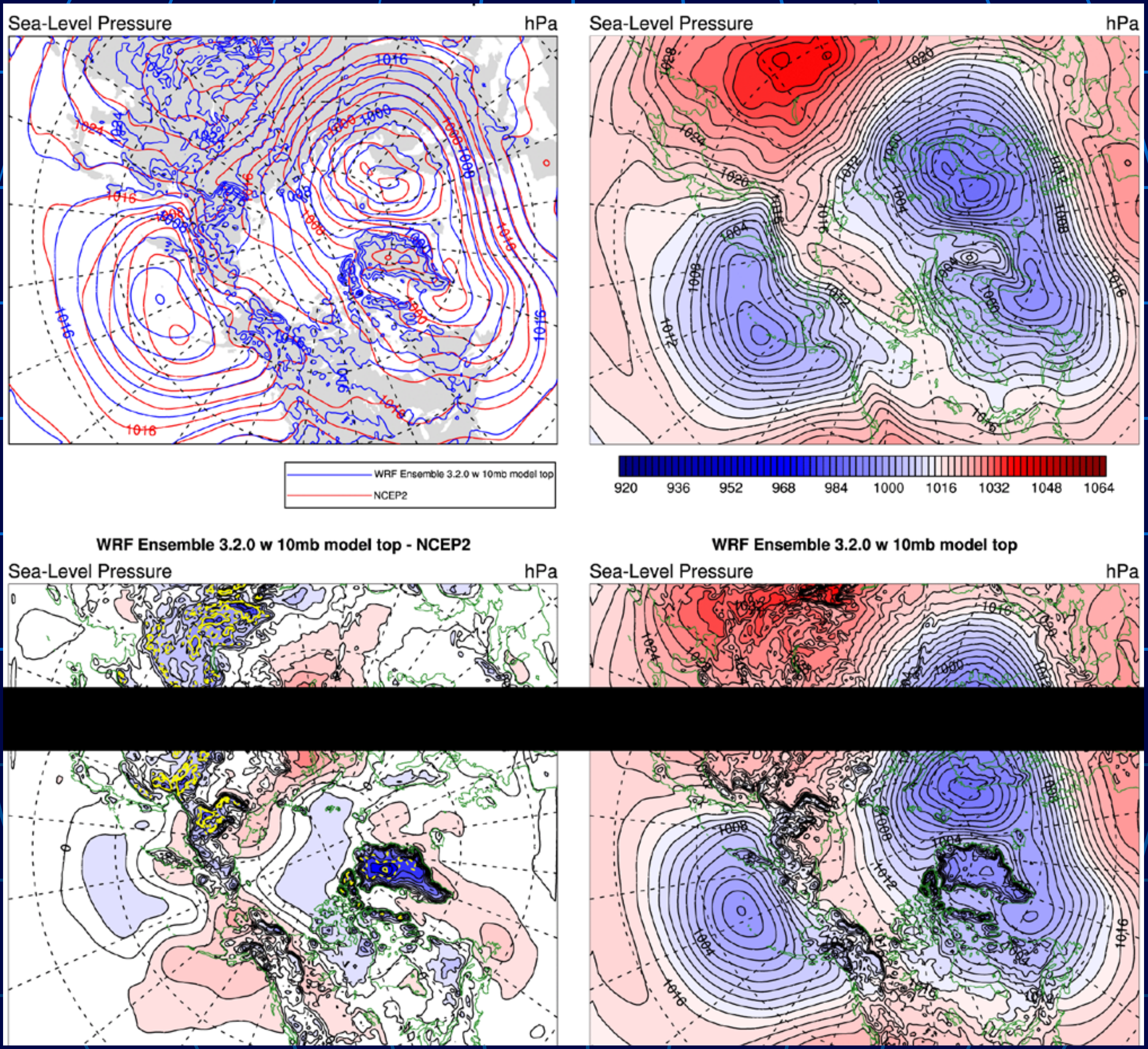
Stand-alone WRF 3.2.0, “best case”, 10 mb top, **no** spectral nudging

Overlay: WRF (blue), NCEP2 (red)

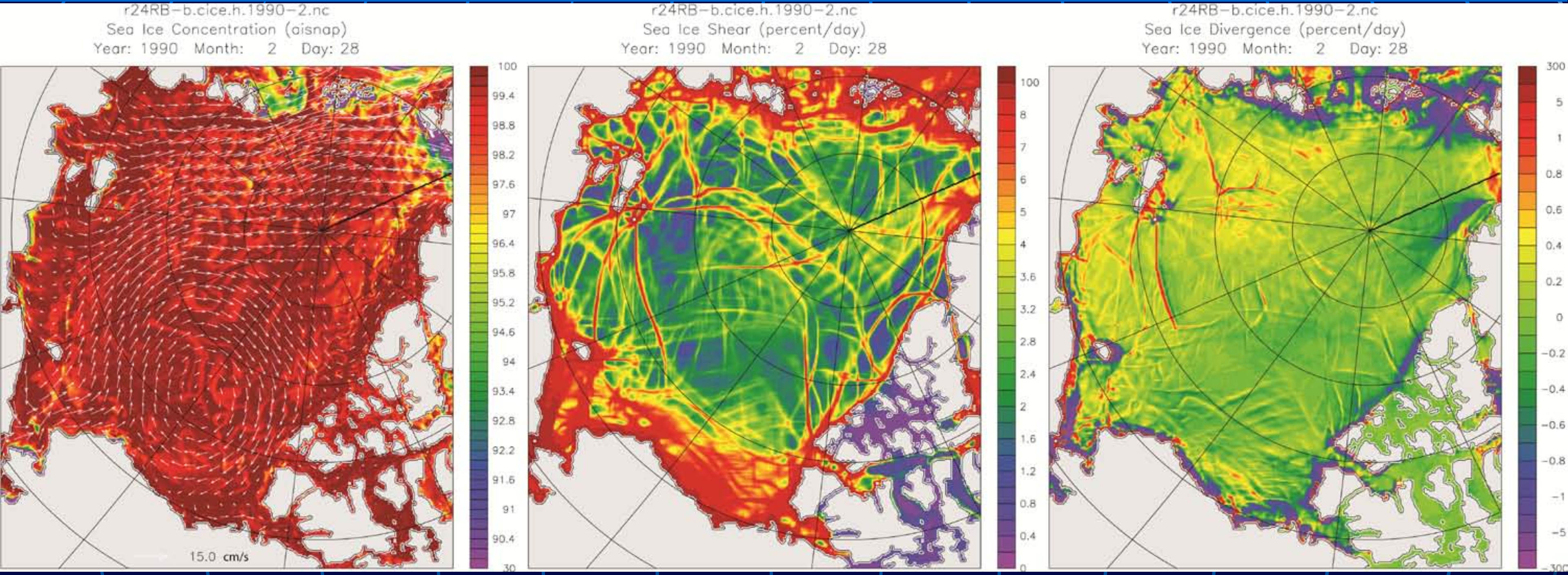
NCEP2

Difference

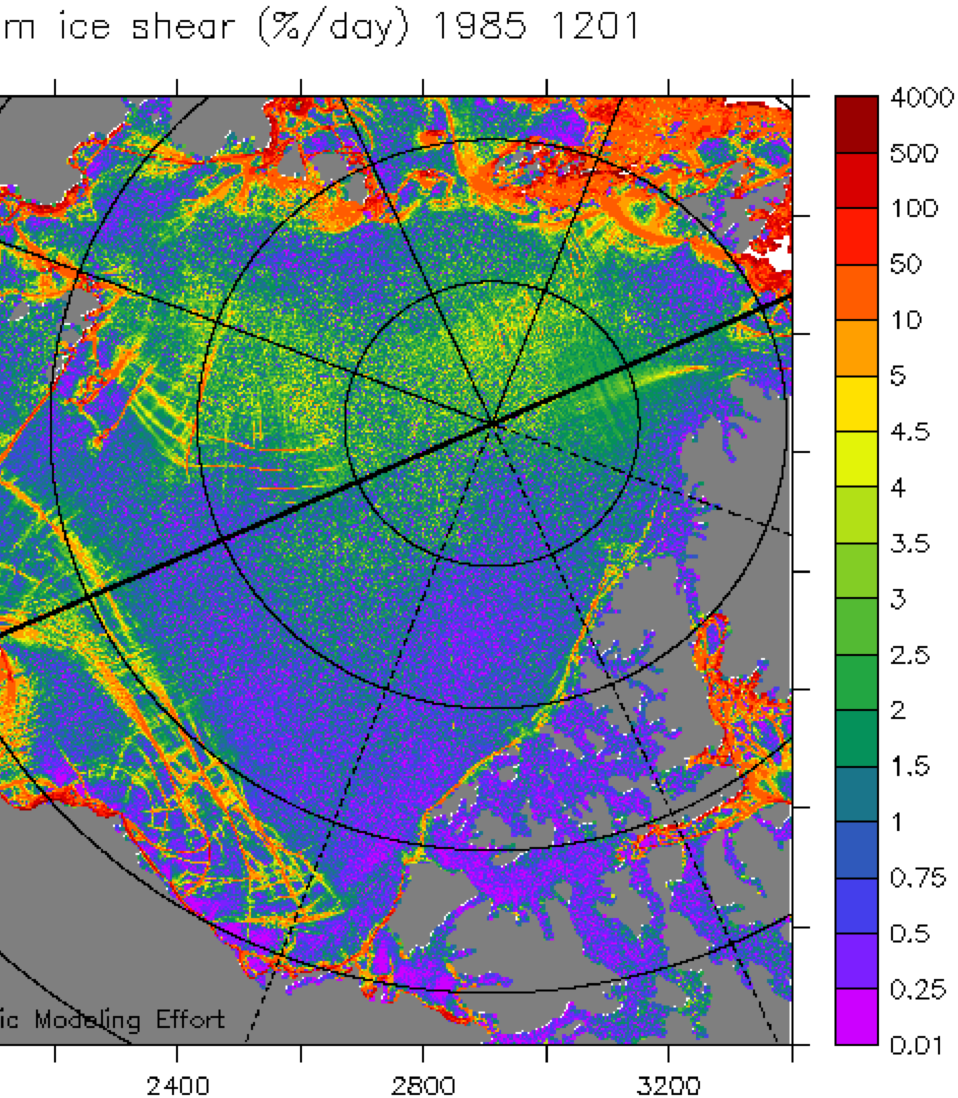
WRF

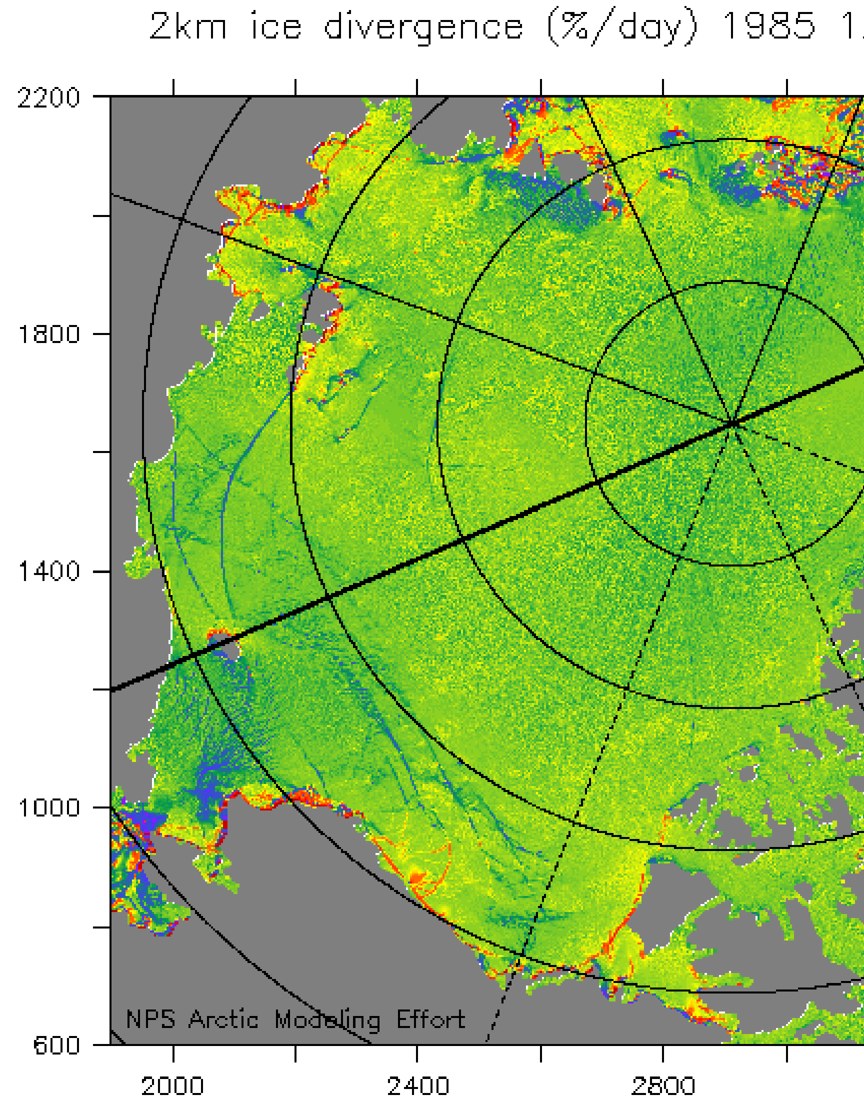


Fully coupled RACM sea ice deformations



- Sea ice drift is affected by ice thickness and affects deformations
- Sea ice divergence and shear affect:
    - air-sea exchange, especially in winter (feedback on atmosphere)
    - thickness distribution
- Both sea ice drift and deformations require realistic high-resolution atmospheric forcing


m ice shear (%/day) 1985 1201
4000
500
100
50
10
5
4.5
4
3.5
3
2.5
2
1.5
1
0.75
0.5
0.25
0.01
2400
2800
3200
ic Modeling Effort


2km ice divergence (%/day) 1985 1
2200
1800
1400
1000
600
2000
2400
2800
NPS Arctic Modeling Effort

Summary

1. Models are getting better in the Arctic Ocean
2. Atmospheric conditions are critical for arctic ice-ocean hindcast & prediction
3. Surface ocean currents and sea ice drift strongly depend on winds and spatial resolution
4. High-resolution is required to represent small-scale ice-ocean processes and forcing
5. Fully coupled and high-resolution regional climate models (e.g. RACM) allow to address the above requirements / limitations
6. RACM – best tool for regional synoptic and climate prediction

"No one trusts a model except the owner.
Everyone trusts data except the owner"

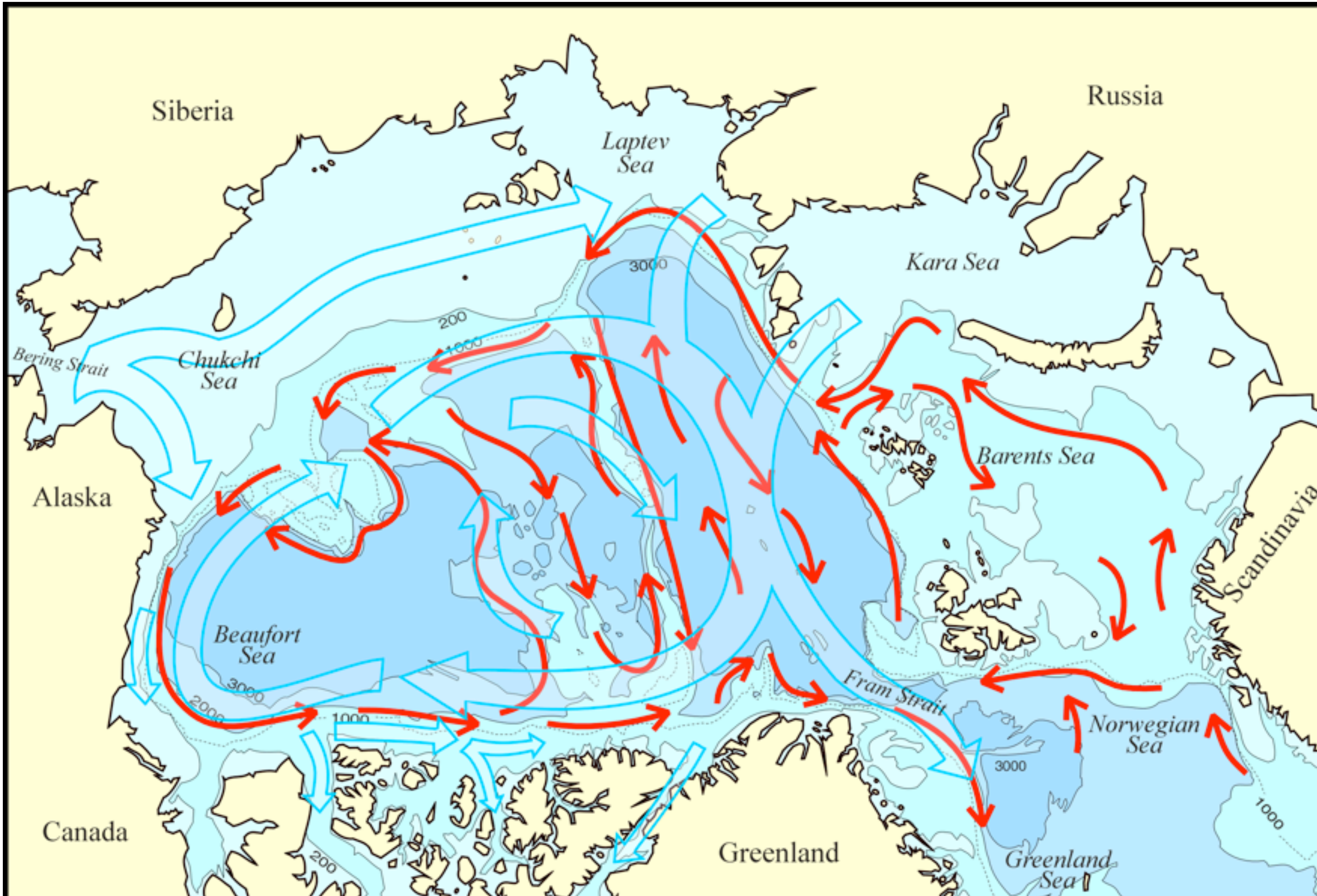
.. a paraphrase by Matt Disney (UCL)
of Harlow Shapley
(1885-1972)

Assessing skill of Arctic ocean-ice models

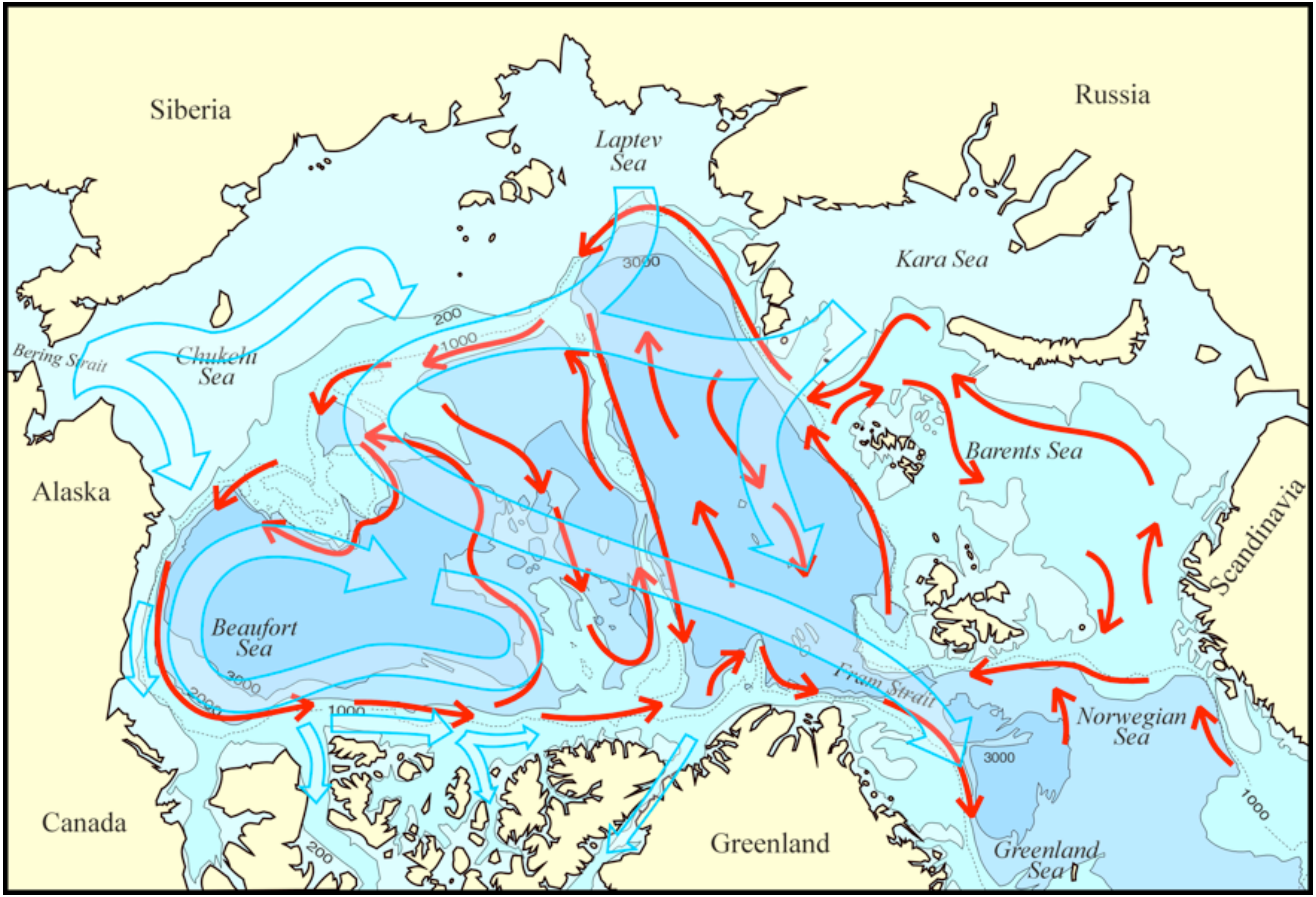
Greg Holloway
Fisheries and Oceans Canada
Institute of Ocean Sciences
Sidney, British Columbia, Canada

for **"Evaluation of the Use of Hindcast Model Data for OSRA in a Period of Rapidly Changing Conditions"**

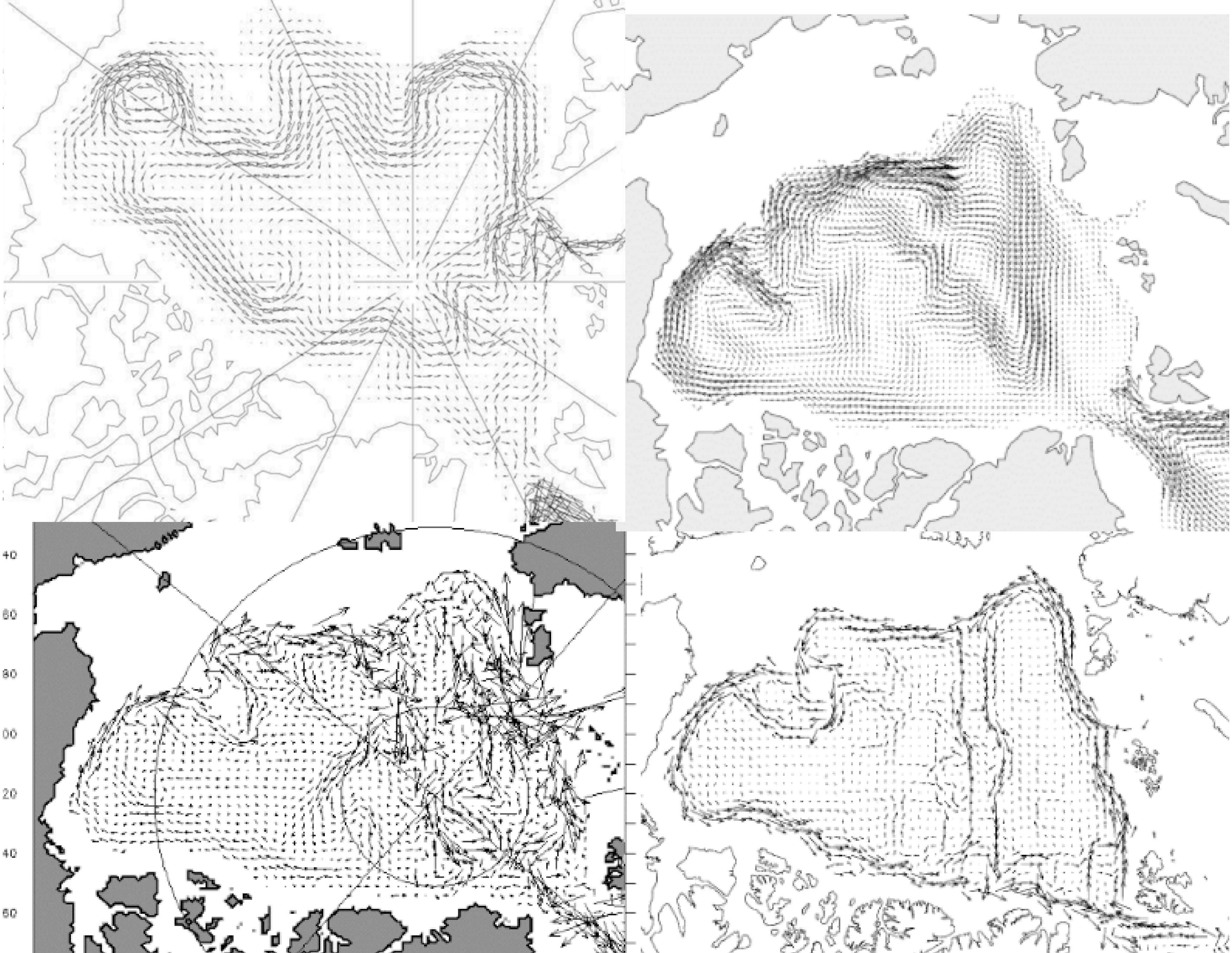
Bureau of Ocean Energy Management, Regulation and Enforcement, 28-31 March 2011



Siberia
Russia
Laptev Sea
Kara Sea
Bering Strait
Chukchi Sea
Barents Sea
Alaska
Scandinavia
Beaufort Sea
Fram Strait
Norwegian Sea
Canada
Greenland
Greenland Sea
3000
200
1000
2000

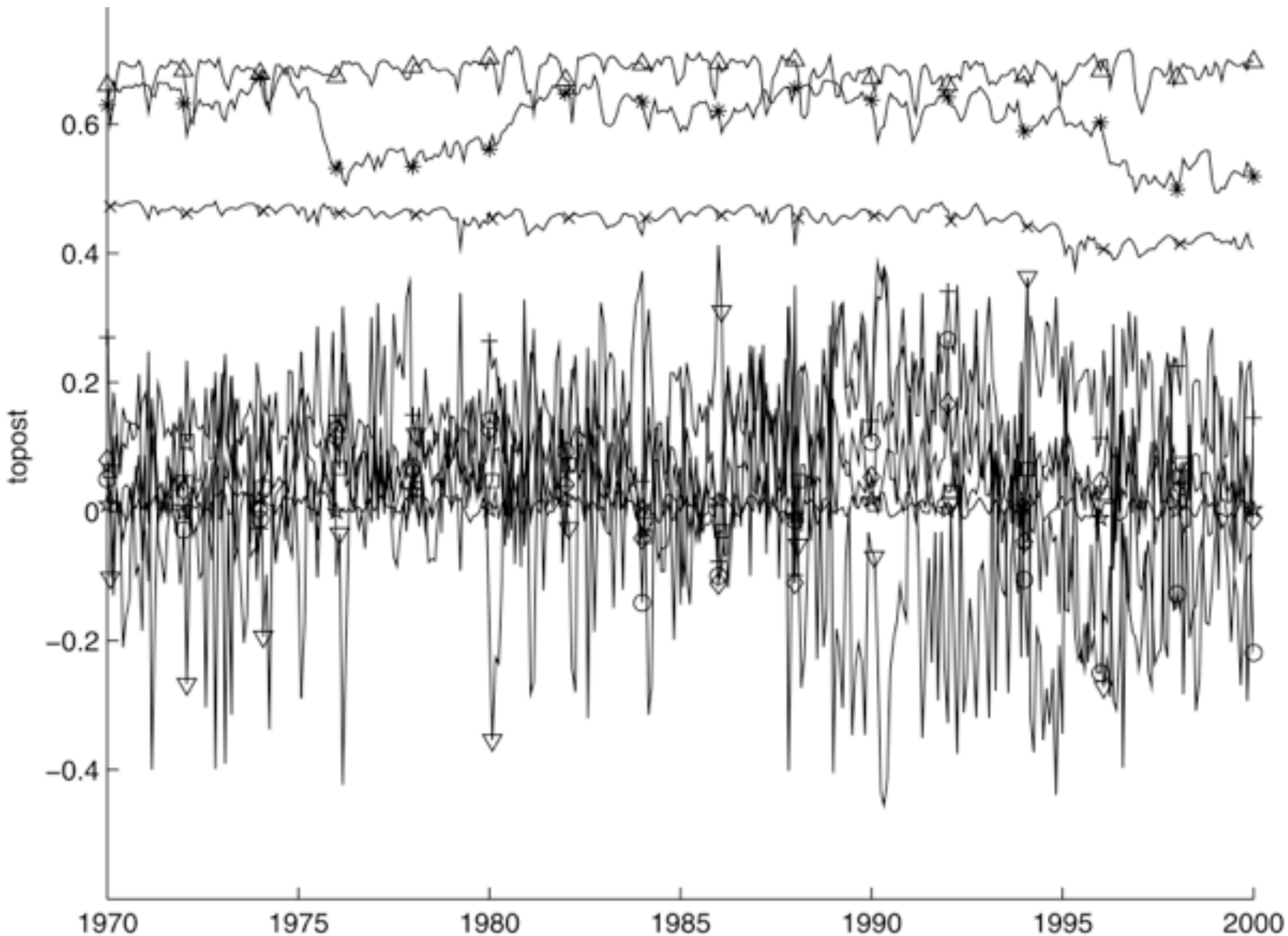


Siberia
Russia
Laptev Sea
Kara Sea
Bering Strait
Chukchi Sea
Barents Sea
Alaska
Scandinavia
Beaufort Sea
Fram Strait
Norwegian Sea
Canada
Greenland
Greenland Sea
200
1000
2000
3000


40
60
80
00
20
40
60

Try to "make sense" from a zillion vector maps: volume averaged topostrophy, $\mathbf{f} \times \mathbf{V} \cdot \nabla D$

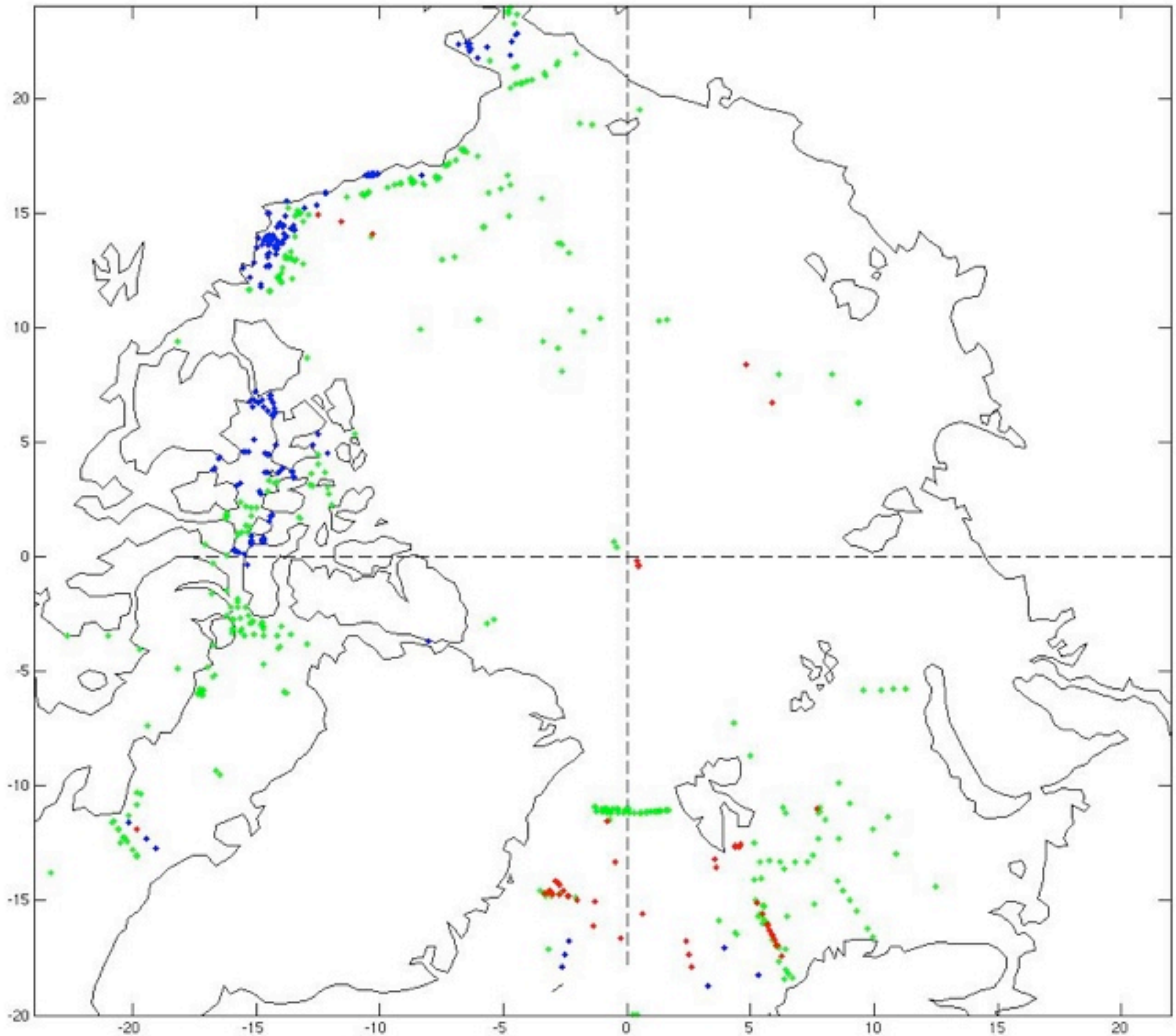
Here were 9 models. *JGR (2007)*



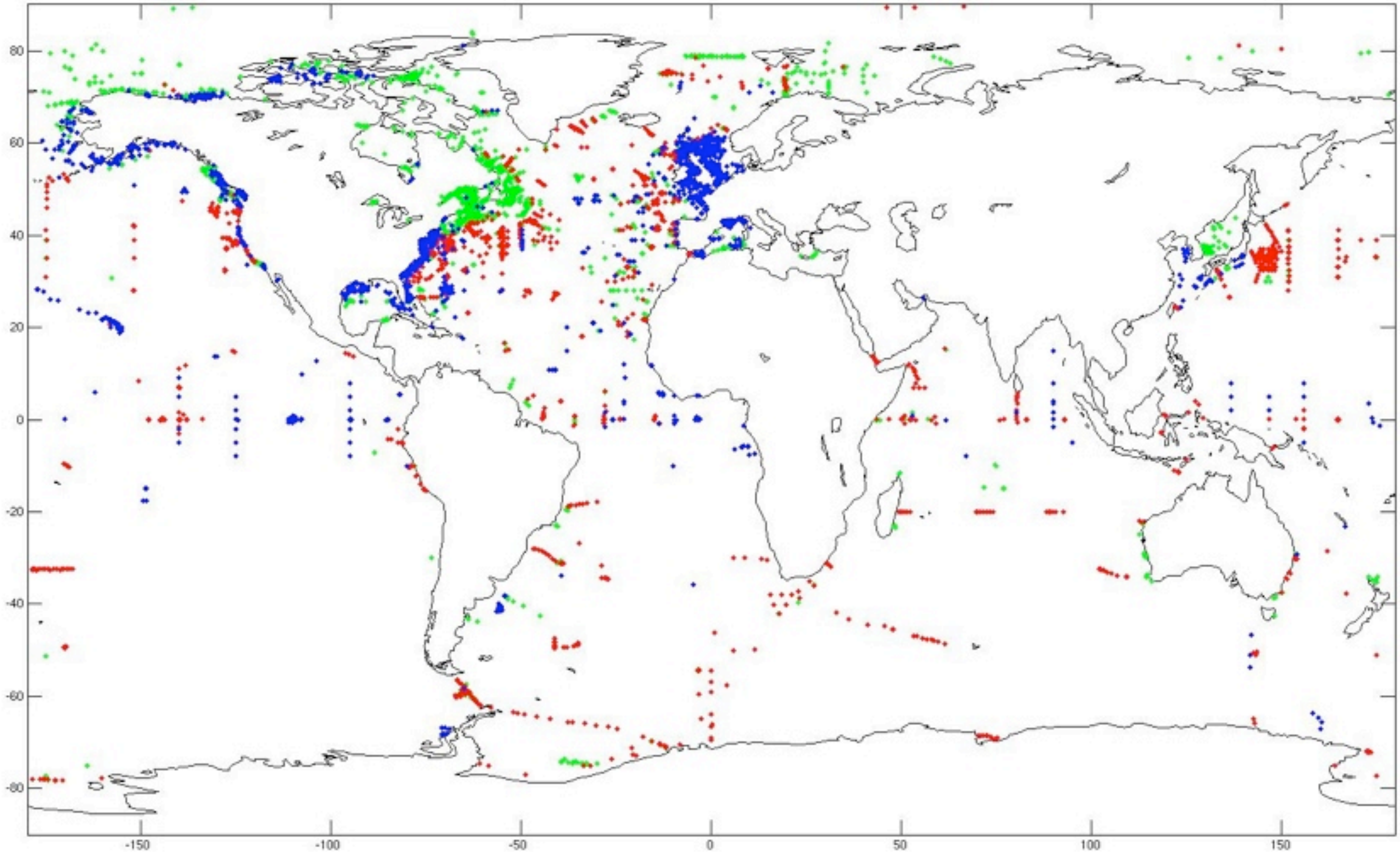
3 models were "weird"

But what is really so?

Can we find enough current meters to test?

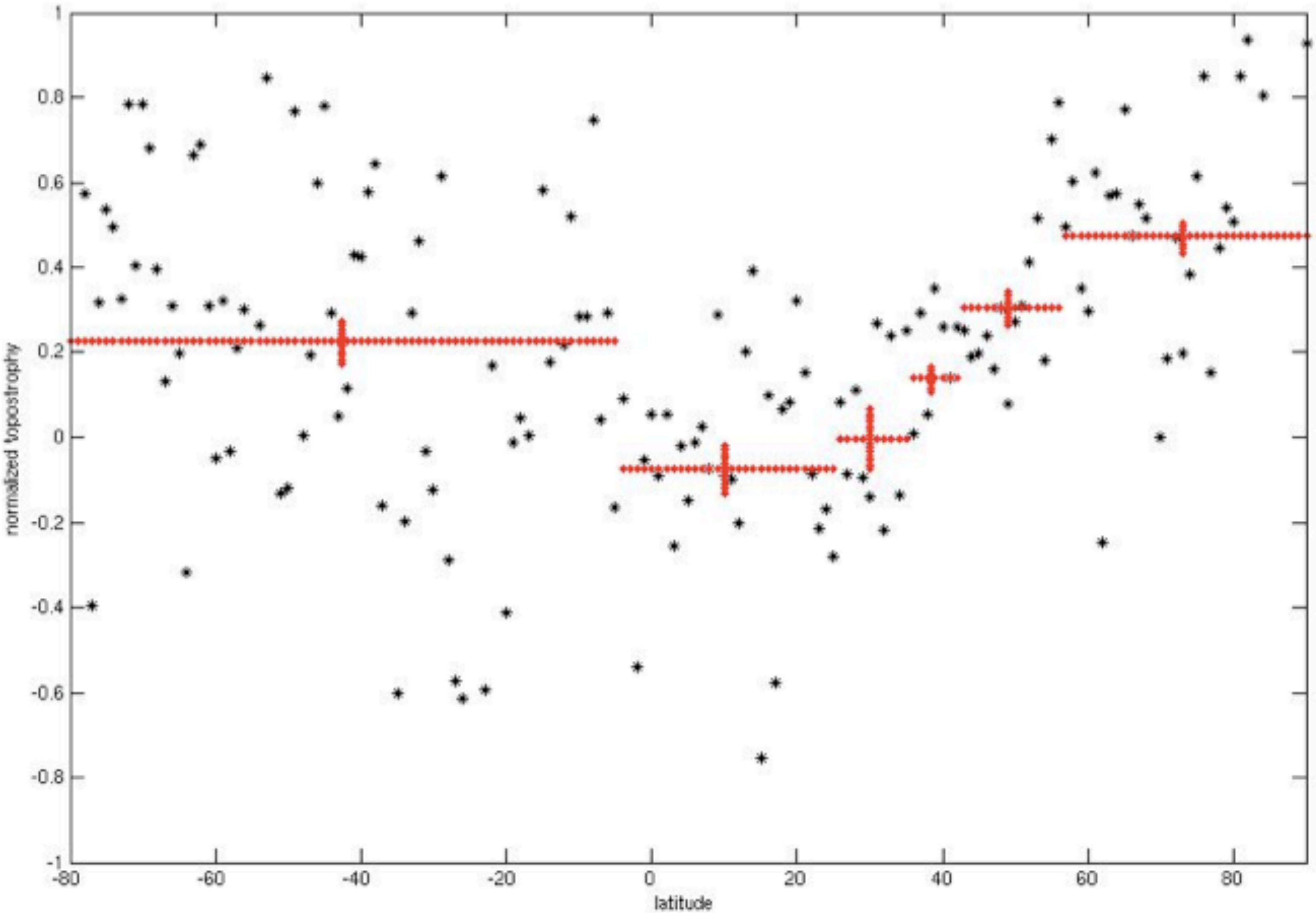


20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20



Humankind's knowledge of ocean over 13000 current-meter-years.

plot $\overline{\mathbf{f}\times\mathbf{V}\cdot\nabla D}\Big/\sqrt{\overline{|\mathbf{f}\times\mathbf{V}|^2}\,\overline{|\nabla D|^2}}$ vs. latitude



Ocean models as seen by current meters

with **An Nguyen**
Massachusetts Institute of Technology, Cambridge, Massachusetts
and **ZeliangWang**
Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia

Nguyen: "ECCO2" at NASA/JPL on 18km, 9km and 4km grids.

Wang: NEMO "ORCA1" at BIO on 1° (nominal) grid.

Two quite opposite approaches:

1) On successively finer grids, try to resolve eddies? *How fine is enough?*

2) On coarse grid, try to parameterize eddy effects. *Lotsaluck?*

Measuring skill (generally): model $= \mathrm{M} + \mathbf{m} + \mathbf{m}'$, observ $= \mathrm{O} + \mathbf{o} + \mathbf{o}'$

M,O are dataset & temporal means. **m**,**o** are pointwise temporal means.

$\mathbf{m}'$, $\mathbf{o}'$ are std. devs. of temporal fluctuations around **m**, **o**.

$$sk1 = \frac{\mathbf{m} \bullet \mathbf{o}}{\sqrt{(\mathbf{m} \bullet \mathbf{m})(\mathbf{o} \bullet \mathbf{o})}} \qquad sk2 = 1 - \frac{\left|\mathbf{m} \bullet \mathbf{m} - \mathbf{o} \bullet \mathbf{o}\right|}{\mathbf{m} \bullet \mathbf{m} + \mathbf{o} \bullet \mathbf{o}} \qquad sk3 = 1 - \frac{|M - O|}{\sqrt{\mathbf{m} \bullet \mathbf{m} + \mathbf{o} \bullet \mathbf{o}}}$$

"$\bullet$" is weighted by duration / temporal variance of fluctuations

Then *skill = (sk1)(sk2)(sk3)*

$skill = 1$ iff model=observed identically

$skill = 0$ if model is random guessing

$skill < 0$ if model is worse than guessing

Do this with anything. Veloc, temperature, salinity, ice, bugs, “ECCO2” at NASA/JPL, test successive grid refinement

Grid (nominal)	18km	9km	4km
Skill (overall)	0.289	0.462	0.478
Topostrophy	0.334	0.469	0.53

nb: topostrophy is not a “skill”. observed topost (2869 pts) = 0.567

NEMO “ORCA1” at BIO, coarse grid, test eddy parameterizations

Friction is eddy viscosity (“as usual”): $A\nabla^2\mathbf{u}$

Neptune forces toward higher entropy: $\mathbf{u}^* \equiv -L^2\mathbf{f}\times\nabla D$

	Friction	Neptune
Skill (overall)	0.087	0.139
Topostrophy	0.426	0.507

Surprise? Topostrophy w/ friction is not-so-bad.
Have a look. ORCA1 at 450m.
Problem: topostrophy (at CMs) is normalized.

Friction

Neptune

We've looked at ocean velocity. What about T and S?

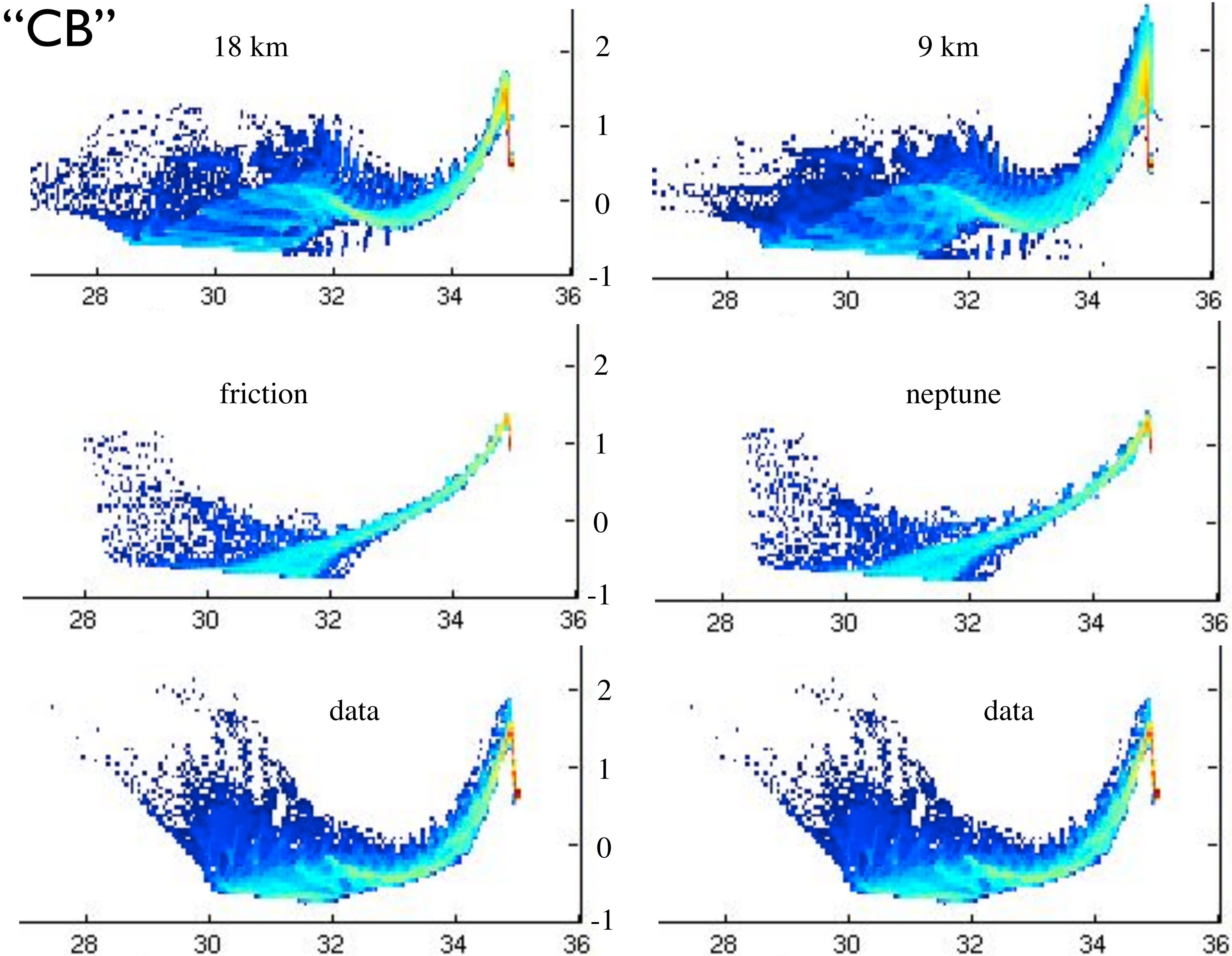
3 slides only from incomplete (paused) work:

Construct volumetric census in T,S space. For each element T<T+dT, S<S+dS, accumulate model vol dV.

Because the nature of T,S varies regionally, separate "the Arctic" into 8 subdomains.

Compare ECCO2 at 18km and 9km.
Compare ORCA1 friction and neptune.


L
CA
CB
C
G
E
M
B



"CB"
18 km
9 km
friction
neptune
data
data
2
1
0
-1
28
30
32
34
36

nb: omitting Skill3 (the mismatch in overall mean log(vol))

ECCO2	18km	9km	ORCA1	friction	neptune
"CB"	0.747	0.657		0.455	0.48
"C"	0.642	0.543		0.297	0.301
"E"	0.761	0.756		0.576	0.636

Conclusions? not really. work in progress. but ...

Suggestions?

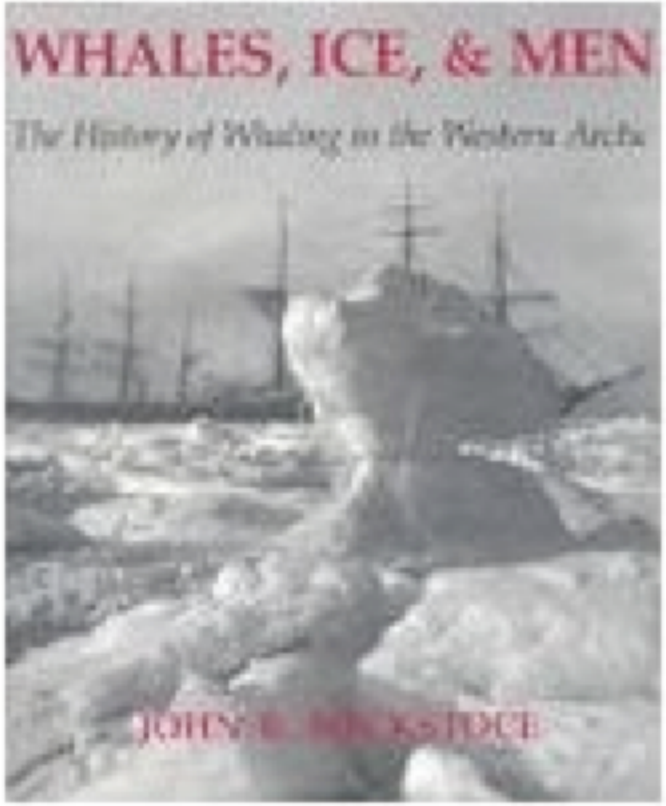
1. Topostrophy $\mathbf{f} \times \mathbf{V} \cdot \nabla D$ as a way of characterizing V
2. Skill measures:

$$sk1 = \frac{\mathbf{m} \bullet \mathbf{o}}{\sqrt{(\mathbf{m} \bullet \mathbf{m})(\mathbf{o} \bullet \mathbf{o})}} \qquad sk2 = 1 - \frac{|\mathbf{m} \bullet \mathbf{m} - \mathbf{o} \bullet \mathbf{o}|}{\mathbf{m} \bullet \mathbf{m} + \mathbf{o} \bullet \mathbf{o}} \qquad sk3 = 1 - \frac{|M - O|}{\sqrt{\mathbf{m} \bullet \mathbf{m} + \mathbf{o} \bullet \mathbf{o}}}$$

No need "climatology". t-depend OK? Ice variables?

Did we learn some things about models?

1. Finer grids can get better answers,
   and maybe 4km (or 2km) is good enough.
2. Eddy theory can help.
   60km model can get 4km answer (a bit blurry) **?**



Whales, Ice, and Men: The History of Whaling in the Western Arctic [Paperback]

John R. Bockstoce (Author)

intermediate layers circulation, from Rudels (2011)