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

Workshop

Science Applications International Corporation
Center for Water Science and Engineering
McLean, Virginia

March 29-31, 2011

SAIC®
From Science to Solutions

Objectives

- Review and analysis of Arctic oceanography
- Describe the effects of climate change in the Arctic and the impacts on circulation
- Describe hindcast data used in the OSRA model for skill assessment
- Evaluate alternatives such as using forecast results in the OSRA model
- Recommend future studies

Agenda

Day 1

- 0830 – 0900 Registration and Check-in (SAIC Conference Center)
- 0900 – 0915 Welcome and Introduction (Dr. William Samuels, SAIC)
- 0915 – 0930 Background and Program Objectives (Dr. Heather Crowley, BOEMRE)
- 0930 – 0945 Workshop Goals (Dr. William Samuels, SAIC)
- 0945 – 1045 Arctic OSRA and Ocean Modeling Overview (Dr. Walter Johnson, BOEMRE)
- 1045 – 1100 Break
- **Session I** - **Observational Trends in Arctic Ocean Datasets**
- 1100 – 1200 Ocean Circulation (Dr. Tom Weingartner, University of Alaska)
- 1200 – 1300 Lunch
- 1300 – 1400 Meteorology (Dr. Xiangdong Zhang, University of Alaska)
- 1400 – 1500 Sea Ice (Dr. Walt Meier, NSDIC)
- 1500 – 1515 Break
- 1515 – 1615 Session I Discussion (Facilitator, David Amstutz, SAIC)
- 1615 – 1630 Summary and Wrap-up (Dr. William Samuels, SAIC)

SAIC From Science to Solutions

Agenda

DAY 2

Session II - Effects of Climate Change on OSRA Model Inputs

- 0800 – 0900 Ocean Circulation (Dr. Michael Steele, APL, University of Washington)
- 0900 – 1000 Ice movement and concentration (Dr. Muyin Wang, University of Washington)
- 1000 – 1015 Break
- 1015 – 1115 Meteorology (Dr. Jing Zhang, NC A&T University)
- 1115 – 1200 Session II Discussion (Facilitator, Dr. David Amstutz, SAIC)
- 1200 – 1300 Lunch
- **Session III – Comparison of Ocean Hindcast/Forecast Model Results**
- 1300 – 1400 Arctic Ocean Model Intercomparrison Project (Dr. Andrey Proshutinsky, WHOI)
- 1400 – 1500 Cross Section of Models - Strengths and Weaknesses (Dr. Andrey Proshutinsky, WHOI)
- 1500 – 1515 Break
- 1515 – 1615 Requirements of Arctic Ocean Hindcast and Forecast Models (Dr. Wieslaw Maslowski, Naval Postgraduate School)
- 1615 – 1630 Summary and Wrap-up (Dr. William Samuels, SAIC)

Agenda

DAY 3

- 0830 – 0930 Model Skill Assessment (Dr. Greg Holloway, Fisheries and Oceans, Canada)
- 0930 – 1045 Session III Discussion (Facilitator, Dr. David Amstutz, SAIC)
- 1045 – 1100 Break
- 1100 – 1200 Summary and Recommendations (Dr. William Samuels, SAIC)
- 1200 – 1300 Lunch
- 1300 – 1500 Scientific Review Panel Meeting with BOEMRE and the SAIC Project Team

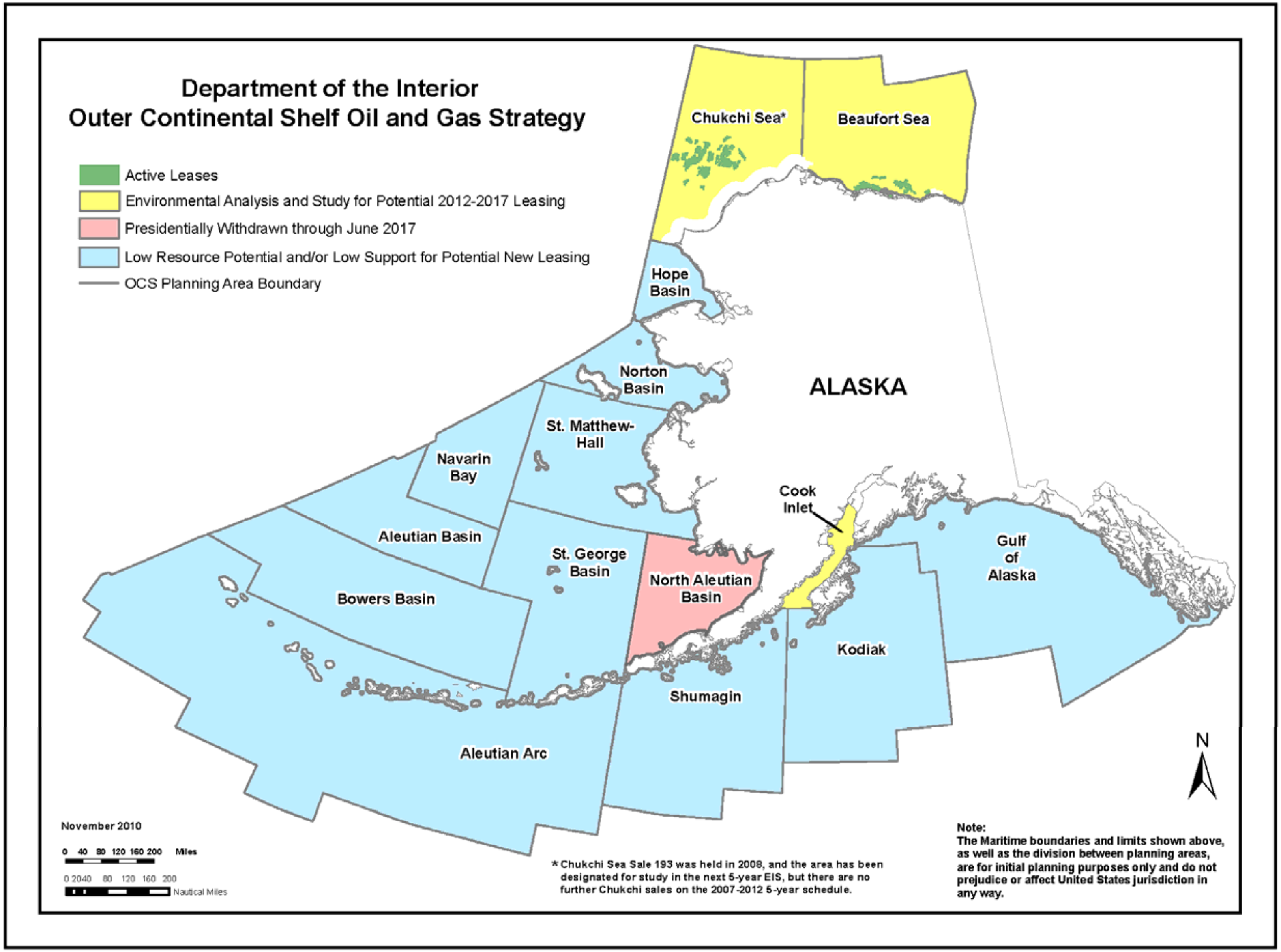
U.S Department of the Interior
Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)

Environmental Program

Heather Crowley, Ph.D.
Oceanographer
Alaska OCS Region

March, 2011

ALASKA OCS


Department of the Interior
Outer Continental Shelf Oil and Gas Strategy
Active Leases
Environmental Analysis and Study for Potential 2012-2017 Leasing
Presidentially Withdrawn through June 2017
Low Resource Potential and/or Low Support for Potential New Leasing
OCS Planning Area Boundary
Chukchi Sea*
Beaufort Sea
Hope Basin
Norton Basin
ALASKA
St. Matthew-Hall
Navarin Bay
Cook Inlet
Aleutian Basin
St. George Basin
North Aleutian Basin
Gulf of Alaska
Bowers Basin
Kodiak
Shumagin
Aleutian Arc
N
November 2010
Miles
Nautical Miles
* Chukchi Sea Sale 193 was held in 2008, and the area has been designated for study in the next 5-year EIS, but there are no further Chukchi sales on the 2007-2012 5-year schedule.
Note:
The Maritime boundaries and limits shown above, as well as the division between planning areas, are for initial planning purposes only and do not prejudice or affect United States jurisdiction in any way.

Agency Mission

To manage the development of ocean energy and mineral resources on the Outer Continental Shelf in a safe and environmentally sound manner.

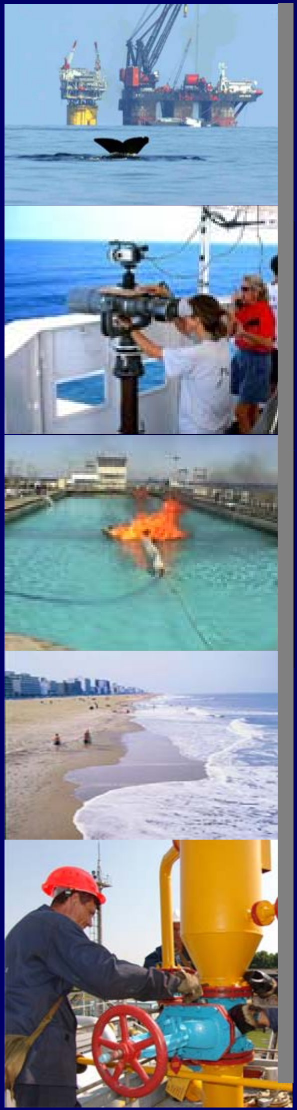
- **Competitively lease tracts to private companies**
- **Oversee and regulate resulting exploration, development and production projects**
- **While protecting the human, marine and coastal environments**

Key Concerns: Subsistence Hunting, Wildlife Protection, Pollution, Noise, Climate Change, Revenue Sharing

Drivers

- **Outer Continental Shelf Lands Act (OCSLA)**
  - Conduct activities on Federal Offshore lands so as to "prevent or minimize damage" to the environment.
- **President's National Energy Policy Report**
  - Challenge: "Increasing energy supply while protecting the environment."
- **Compliance with environmental statutes**
  - NEPA, ESA, MMPA, MSFCMA, CWA, CAA
- **2007-2012 Interior Strategic Plan**
  - "Manage or influence resource use to enhance public benefit, responsible use and economic value (energy)."

Critical Elements



Environmental Assessment Program

www.boemre.gov/eppd/assessment/index.htm

Environmental Studies Program

www. boemre.gov/eppd/sciences/esp/index.htm

Oil Spill Modeling Program

www. boemre.gov/eppd/sciences/osmp/index.htm

Coastal Impact Assistance Program

www. boemre.gov/offshore/CIAPmain.htm

Environmental Evaluation

Large

GEOGRAPHIC AREA

Small

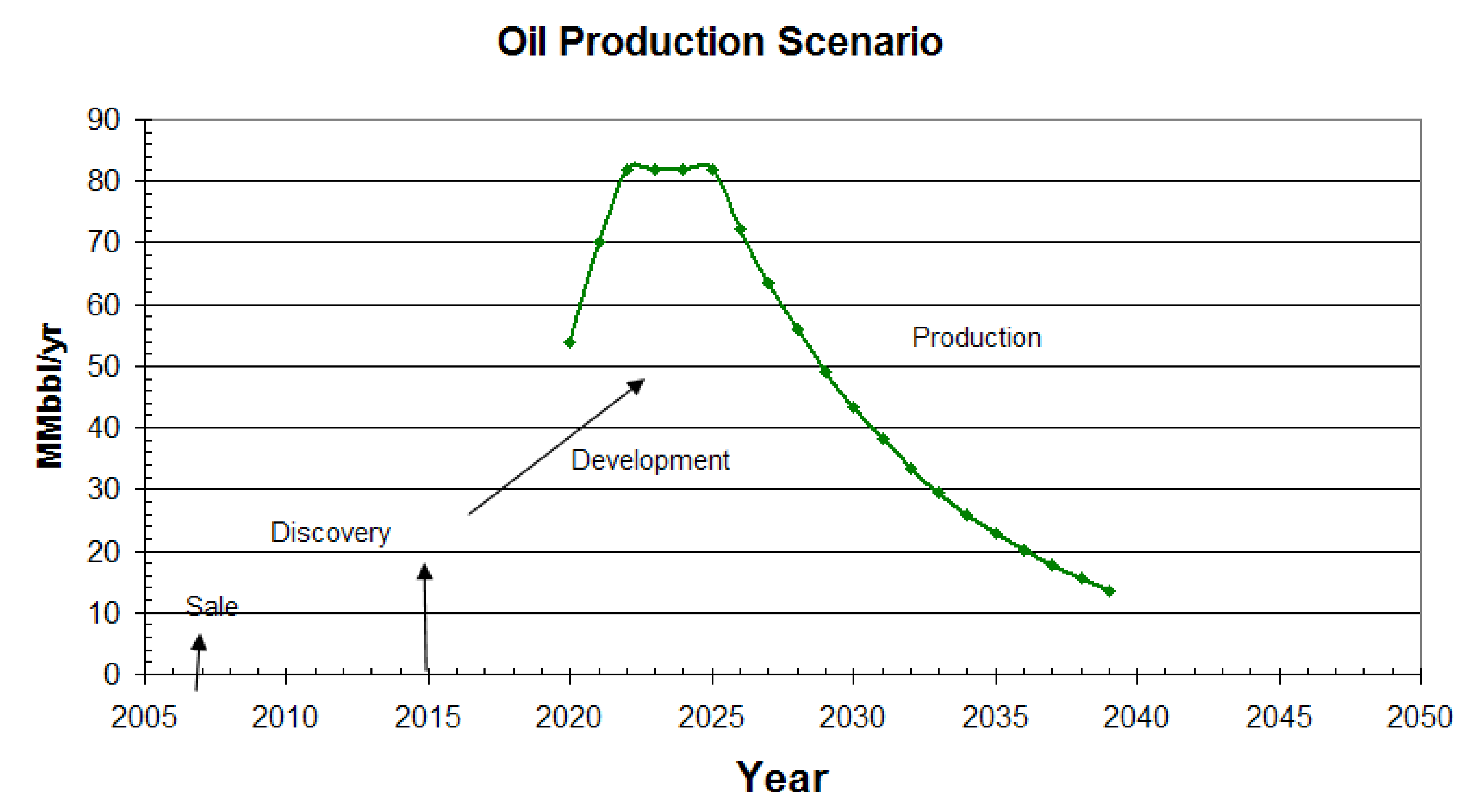
5 Year Program – Nationwide

Lease Sale – Region Specific

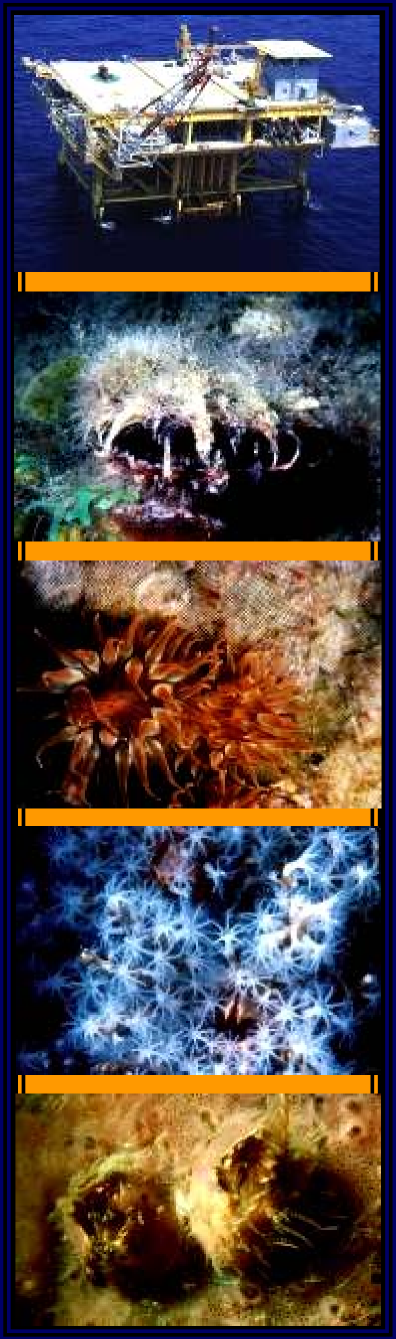
Exploration Plan – Specific Project

Development Plan Specific Platform(s)

** also develop activity-specific NEPA documents (seismic surveys, ancillary activities)



Oil Production Scenario
MMbbl/yr
90
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Year
Sale
Discovery
Development
Production



Environmental Studies Program Mission

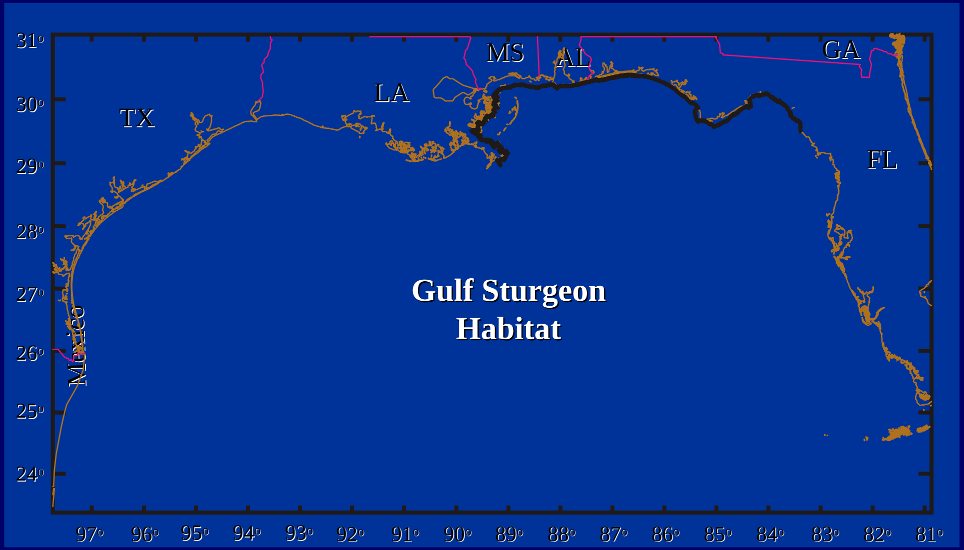
To provide the information needed to predict, assess and manage impacts from offshore energy and marine mineral exploration, development and production activities on human, marine and coastal environments.

Examples of Environmental Research

- Adaptation of Arctic Circulation Model
- Surface Current Circulation HF Radar in the Arctic Ocean
- Updates to the Fault Tree for Oil-Spill Occurrence Estimators
- Hanna Shoal Ecosystem Study
- Fish Monitoring Surveys in the Beaufort Sea
- Monitoring the Distribution of Arctic Whales: Bowhead Whale Aerial Survey Project (1982-present)
- Bowhead Satellite Tagging Study
- Offshore Subsistence Harvest Mapping: Cross Island Whaling 2001-08

Oil Spill Modeling Program

- Estimation of oil-spill risks associated with offshore production, addressing likelihood of spill occurrence and transport and fate of spilled oil
- Oil-Spill Risk Analysis (OSRA) model combines probability of spill occurrence with statistical description of hypothetical oil-spill movement on ocean surface



Technology Assessment and Research (TAR) Program

- Oil and Gas Operational Safety and Engineering Research (OSER)
- Oil Spill Response Research (OSRR) – including Ohmsett Oil Spill Response and Renewable Energy Tank
- Renewable Energy Research

Bureau of Ocean Energy Management, Regulation, and Enforcement

Oil Spill Risk Analysis Introduction

Evaluation of the use of Hindcast model data for OSRA Workshop,

McLean, VA

March 29, 2011

Presentation Objectives

- Describe the technical methods of the Oil Spill Risk Analysis (OSRA) model and its uses in EIS and other documents .
- Provide context for discussion of concerns with the OSRA and how improvements of the OSRA modeling process can be achieved.

NEPA Process of Environmental Protection

Federal Water Pollution Control Act

Marine Mammal Protection Act

National Historic Preservation Act

E.O. 12898: Environmental Justice

NEPA Process

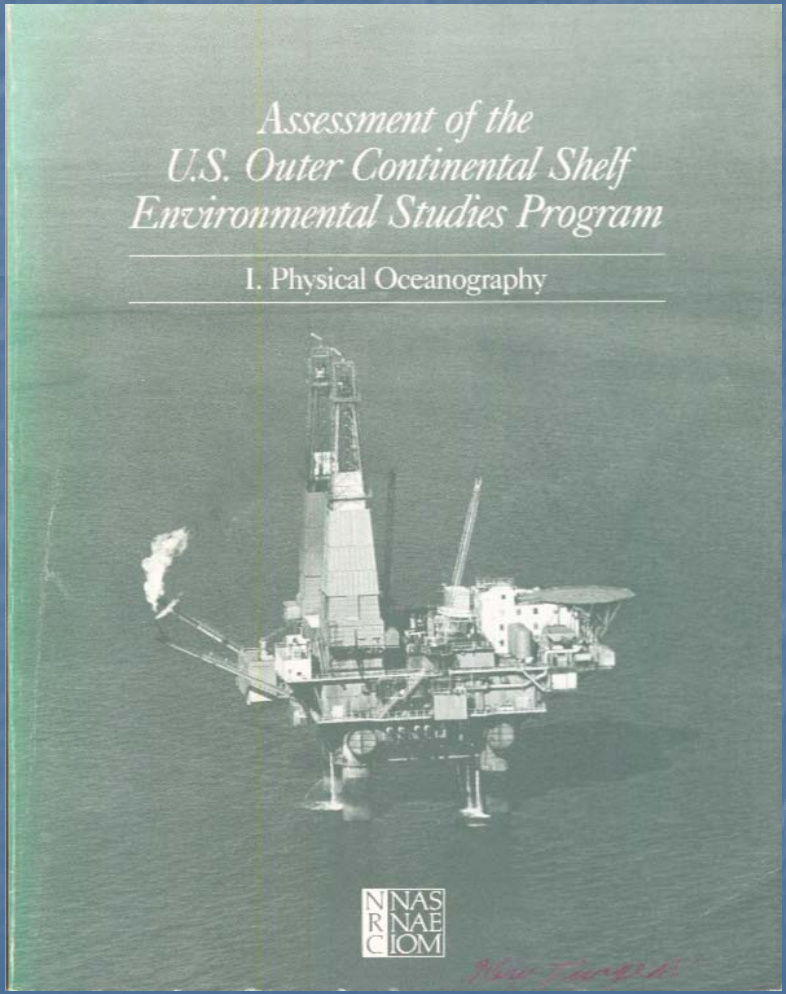
Clean Air Act

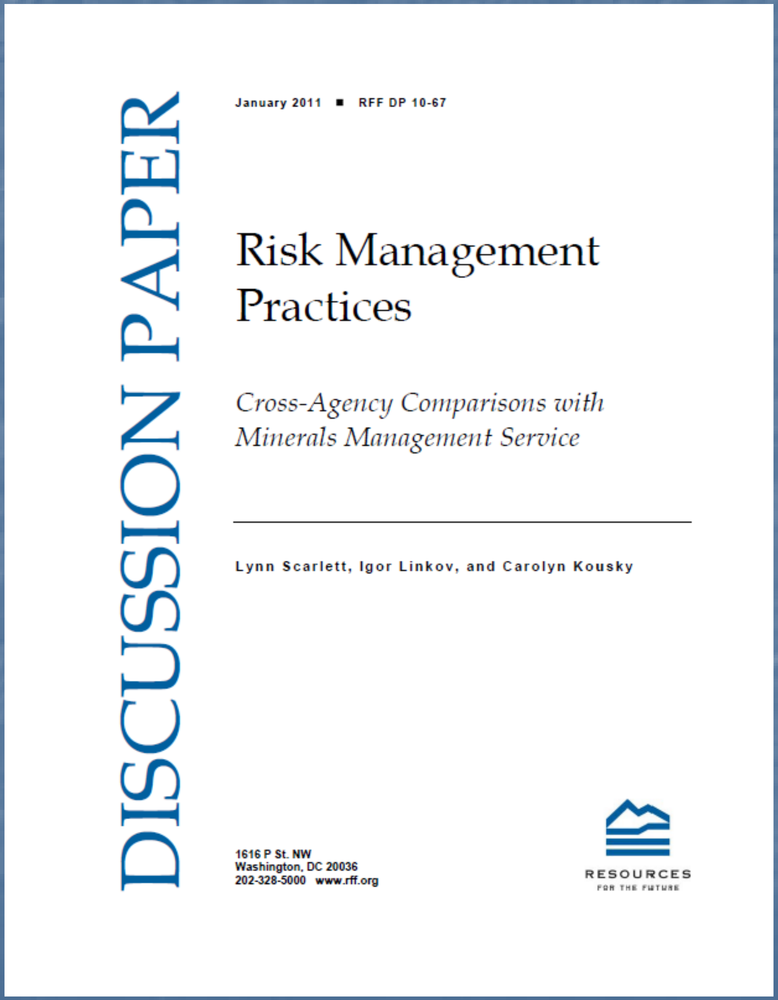
Coastal Zone Management Act

Magnuson-Stevens Fishery Conservation and Management Act

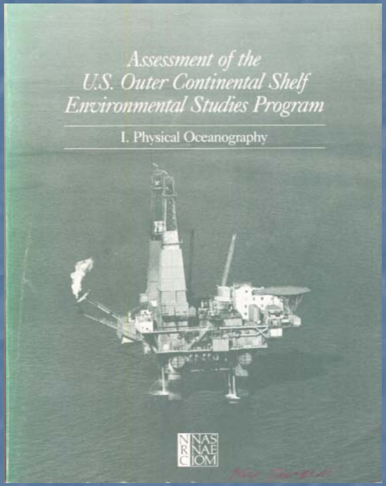
Endangered Species Act

External Reviews of OSRA





NRC Report OSRA



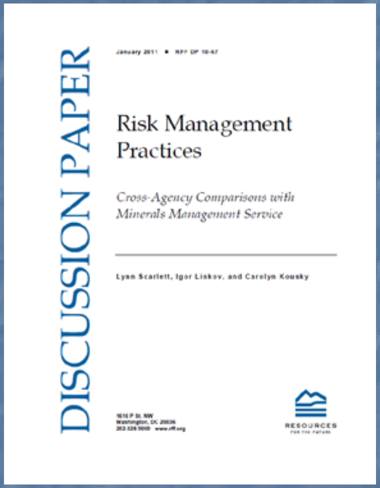
1. Perform risk analysis using observed ocean current data. Reduce the over-reliance on numerical ocean circulation model results until these models are proven.

2. Use winds created by atmospheric models to achieve realistic spatial structure. Use currents derived from ocean models forced by the same gridded winds used for the oil transport.

3. Include empirical weathering and dispersion components to the oil movements.

4. Include random velocity components to the oil movement to simulate turbulent processes.

Oil Spill Commission Discussion Paper



1. The Oil Spill Risk Model has been subject to various technical and analytical critiques and has undergone numerous upgrades and periodic efforts to validate projections of spill trajectories and potential effects. Such efforts have been both regular and transparent.

2. In its 2004 oil-spill risk analysis, BOEMRE used a hazard-based assessment to attempt to better understand the effects of a spill. It is not clear, however, how this information was used in subsequent planning or Endangered Species Act consultation documents.

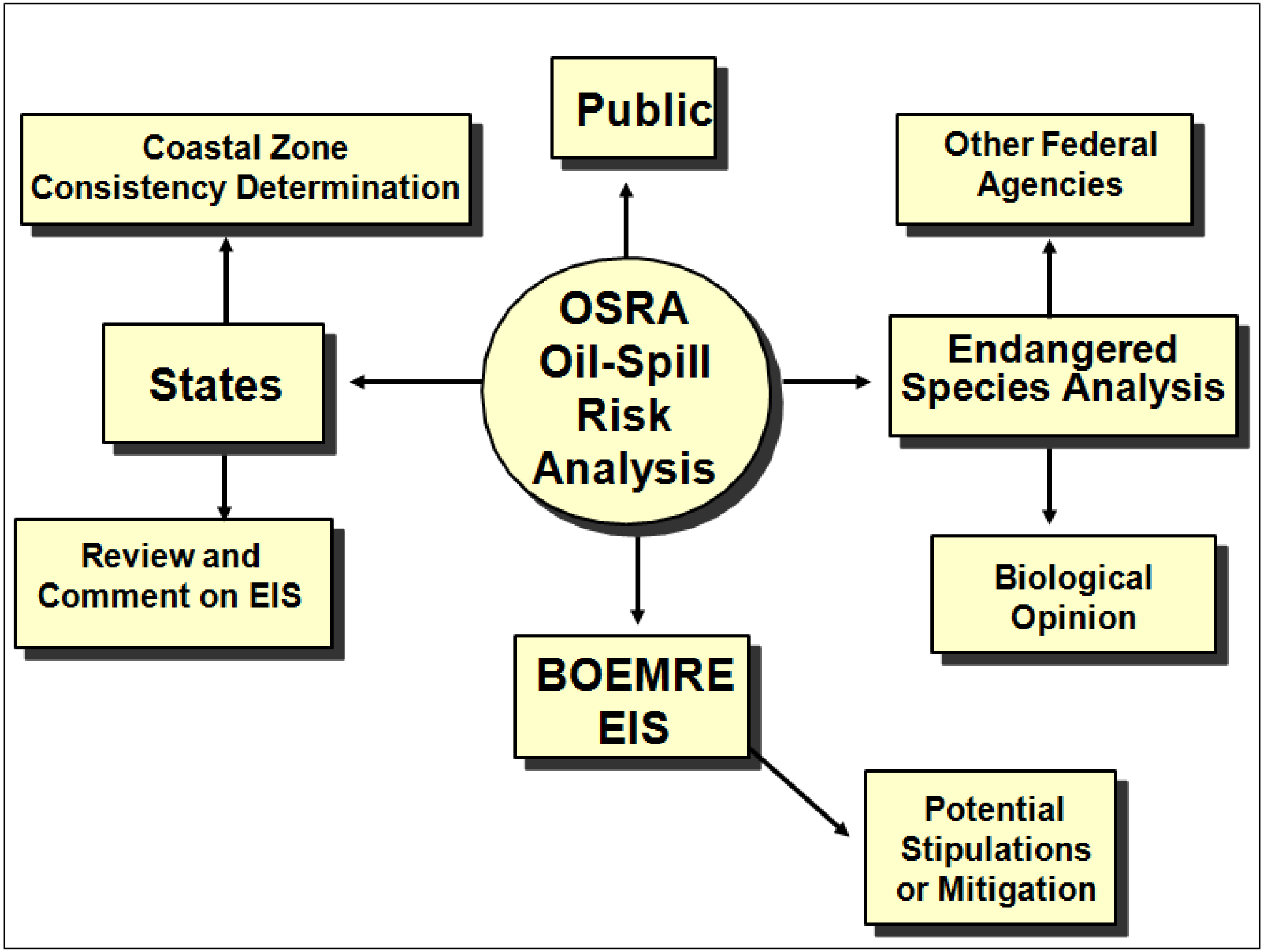
Oil Spill Risk Analysis

- NEPA analysis is performed using "best available" information, not perfect.
- NEPA assumptions are "conservative" for the environment.

BOEMRE Oil Spill Modeling Program

- Assesses oil-spill risks associated with offshore energy activities off the U.S. continental coast and Alaska.
- Oil-Spill Risk Analysis (OSRA) model combines the probability of spill occurrence with a statistical description of hypothetical oil-spill movement on the ocean surface.

Oil Spill Modeling Program



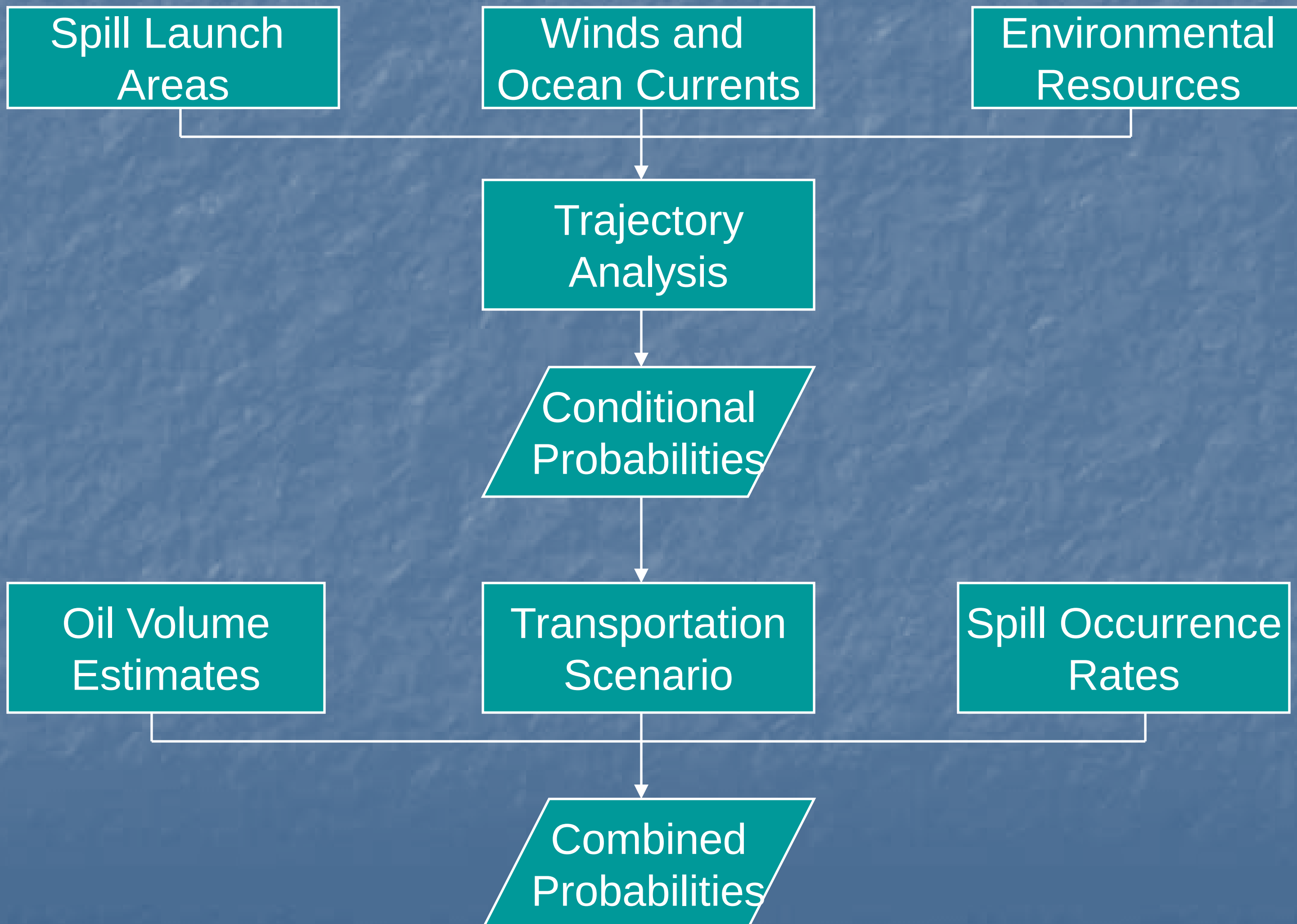
Oil Spill Risk Analysis

- Used in Lease Sale EIS
- Used in Oil Spill Response Plans
- Recognizes that oil spills are an issue for public, even if rare.
- Estimates probability of future spills.
- Estimates paths of the spills and statistically summarizes them.

Oil Spill Probabilities

- What is the probability of oil spills occurring as a result of some action?
  - Historic data (Anderson & LaBelle, 1990, 1994, 2000)
  - Estimated oil production/transportation in the Sale
- What are the chances that spilled oil, driven by winds and currents, will contact shoreline/environmental resources?
  - OSRA trajectory model

OSRA Process



Recent OCS Oil or Condensate Spills

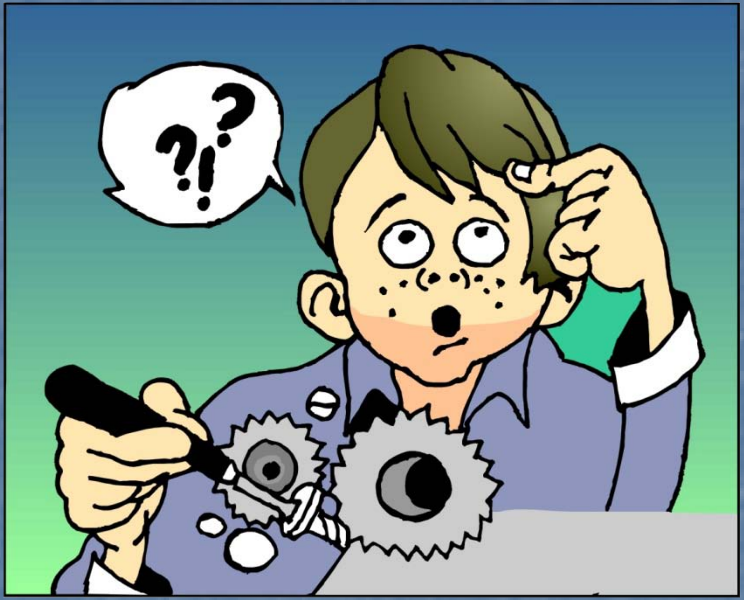
Petroleum Spills of 1,000 barrels and Greater from OCS Facilities, 2002-2010			
Date	Total Spillage	Crude Oil & Condensate	Incident
	barrels	barrels	
2002-2003			
9/15/2004	1,720	1,720	Hurricane Ivan - mudslide buried 6" oil pipeline Seg #7296 (DOI) (oil may still be contained in the damaged segment) Crude Oil
2005			
9/24/2005	2,000	2,000	Hurricane Rita - Platform J destroyed, lost oil on board and in riser (Condensate)
9/24/2005	1,494	0	Hurricane Rita - Jack-up Rig Rowan Fort Worth swept away, never found, lost oil on board, Diesel
9/24/2005	1,572	0	Hurricane Rita - Jack-up Rig Rowan Odessa legs collapsed. Diesel
2006-2007			
9/13/2008	1,316	1,316	Hurricane Ike - 42" gas pipeline Seg #7364 (DOT) parted, probable anchor damage, Condensate
7/25/2009	1,500	1,500	20" oil pipeline Seg #4006 (DOT) - under investigation
4/21/2010	4.9 M	4.9 M	BP - Transocean Deepwater Horizon
SOURCE	Pipeline		Well, Platform or Rig

Occurrence Estimators Used for Alaska by BOEMRE

- Historical Accident Occurrence Rates
- Fault Tree Analysis

Why Use a Fault Tree?

- There are little or no historical large oil spill data in the Offshore Arctic.



Arctic Technological Issues

Ice mechanics

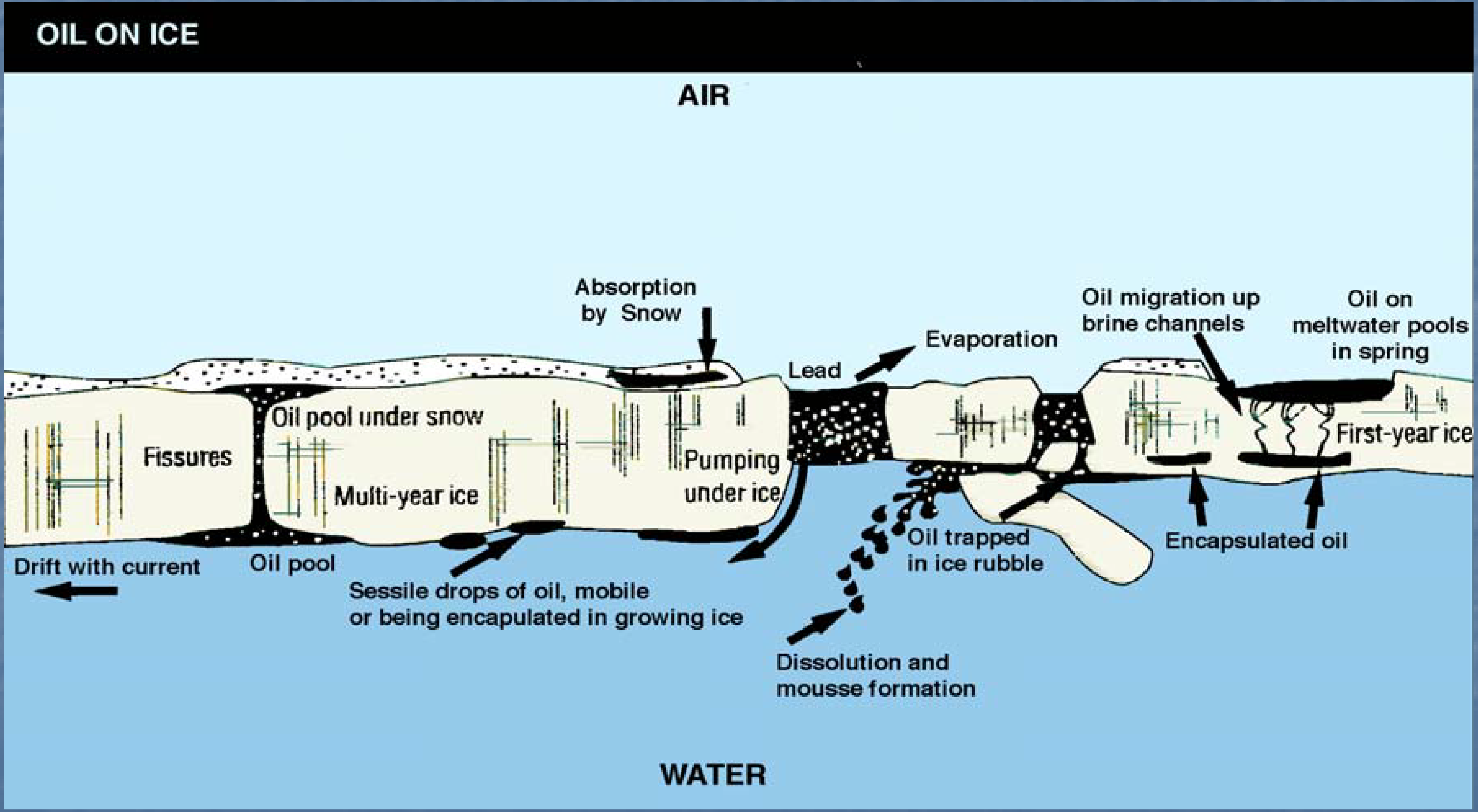
* Icebergs
* Ice pounding
* Ice gouging & Strudel scour

Cold temperatures
Limited construction windows
Pipeline/Soil interactions
Thaw settlement

Arctic Ice Processes

Northstar Island, January, 2008

Arctic Spilled Oil Processes

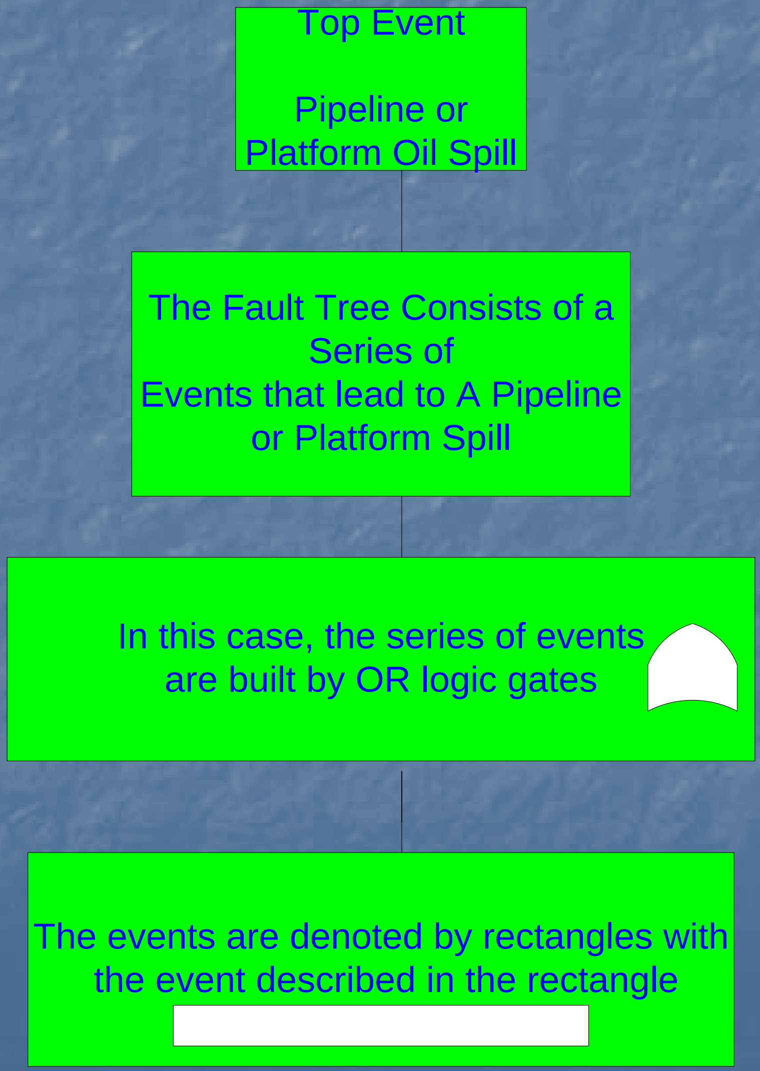


Arctic Effects

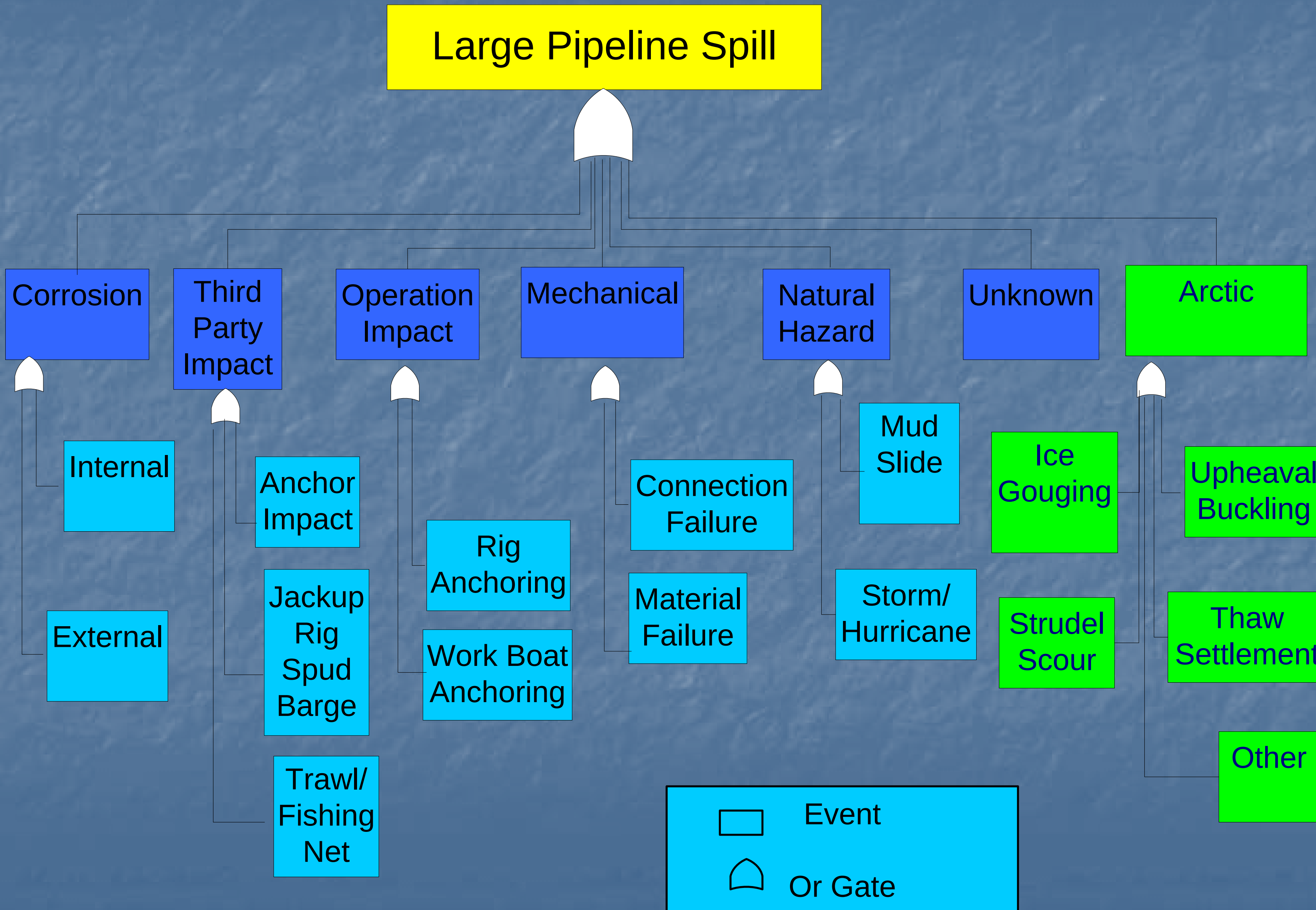
Modification of Existing Causes		Arctic Unique
CORROSION	**OPERATION IMPACT**	**ICE GOUGING**
External	Rig Anchoring Work	
Internal	Boat Anchoring	**STRUDEL SCOUR**
THIRD PARTY IMPACT	**MECHANICAL**	
Anchor Impact	Connection Failure	**UPHEAVAL BUCKLING**
Jackup Rig or Spud	Material Failure	
Barge Trawl/Fishing Net	**NATURAL HAZARD**	**THAW SETTLEMENT**
	Mud Slide	
	Storm/Hurricane	**OTHER**

Fault Tree Analysis

- A method for estimating probability of occurrence of events resulting from interactions of other events



Example Pipeline Fault Tree



Gulf of Mexico Spill Occurrence Rates,
Spills per Volume produced or transported

Oil Spill Rates Based on 1985-1999 Data (Anderson and LaBelle, 2000)		
Spill Source	No. of Spills ≥ 1,000 bbl	No. of Spills ≥ 10,000 bbl
OCS Platforms	0.13 spills/Bbbl	0.05 spills/Bbbl
OCS Pipelines	1.38 spills/Bbbl	0.34 spills/Bbbl
OCS Tankers	0.72 spills/Bbbl	0.25 spills/Bbbl

Anderson and LaBelle, 2000

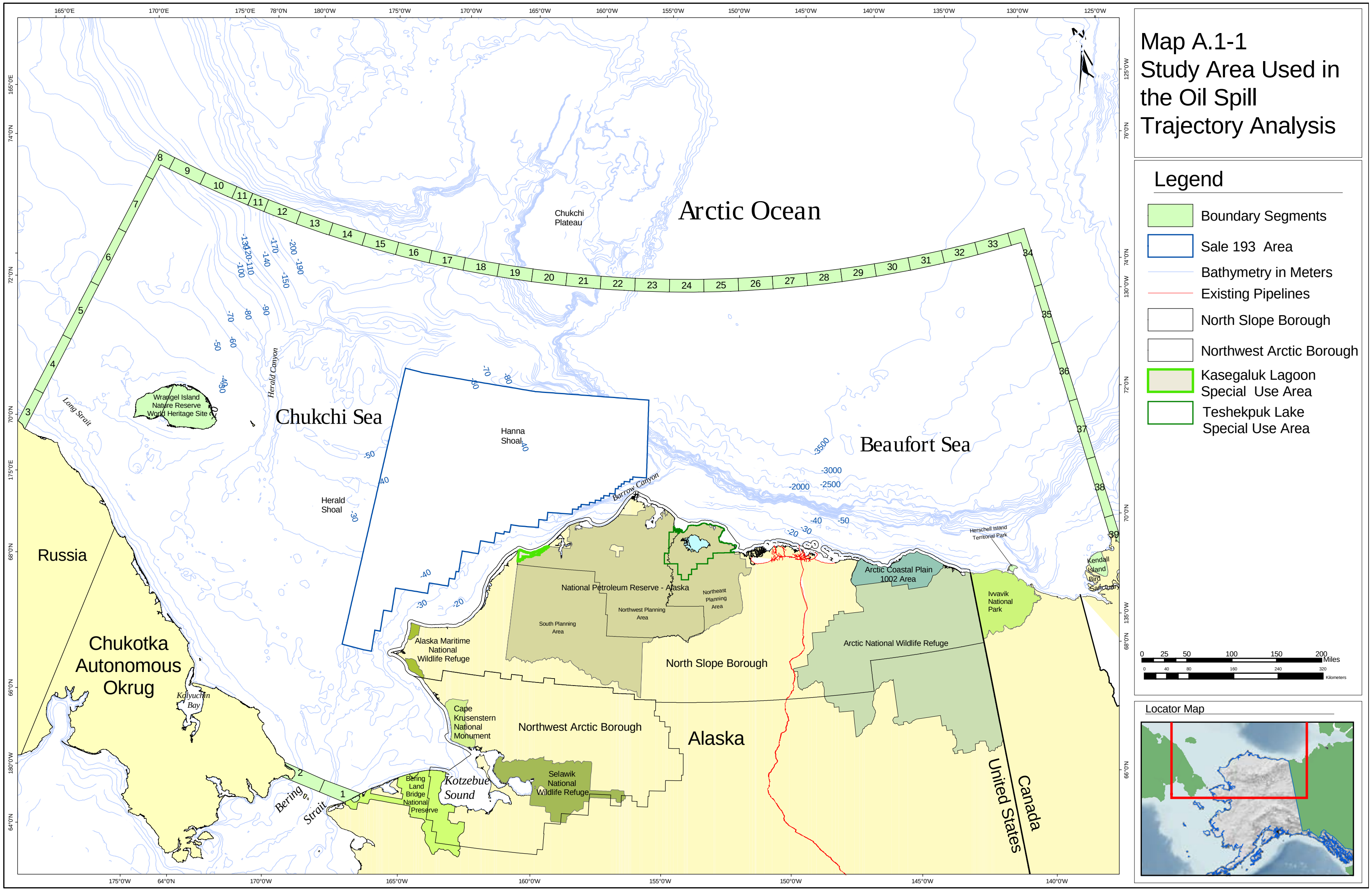
Fault Tree: Spill Rates for Chukchi

- Platforms 0.21 spills per billion barrels produced
- Pipelines 0.30 spills per billion barrels produced
- Platform and Pipeline 0.51 spills per billion barrels produced (95% confidence interval 0.32-0.77 spills per billion barrels)

Chukchi Spill Occurrence Probability, Spills > 1,000 Bbls, Table A.1-25

Lease Sale	Volume, Billion Barrels	Estimated Mean number of spills	Probability of one or more spills (%)
Proposed Action			
Proposed Action (95% Conf. Int.)	1.00	0.51 (0.30-0.77)	40% (27-54%)
Alternatives			
Corridor I	0.60	0.33 (0.20-0.49)	28% (18-39%)
Corridor II	0.76	0.43 (0.27-0.65)	35% (24-48%)

Base Map Study Area



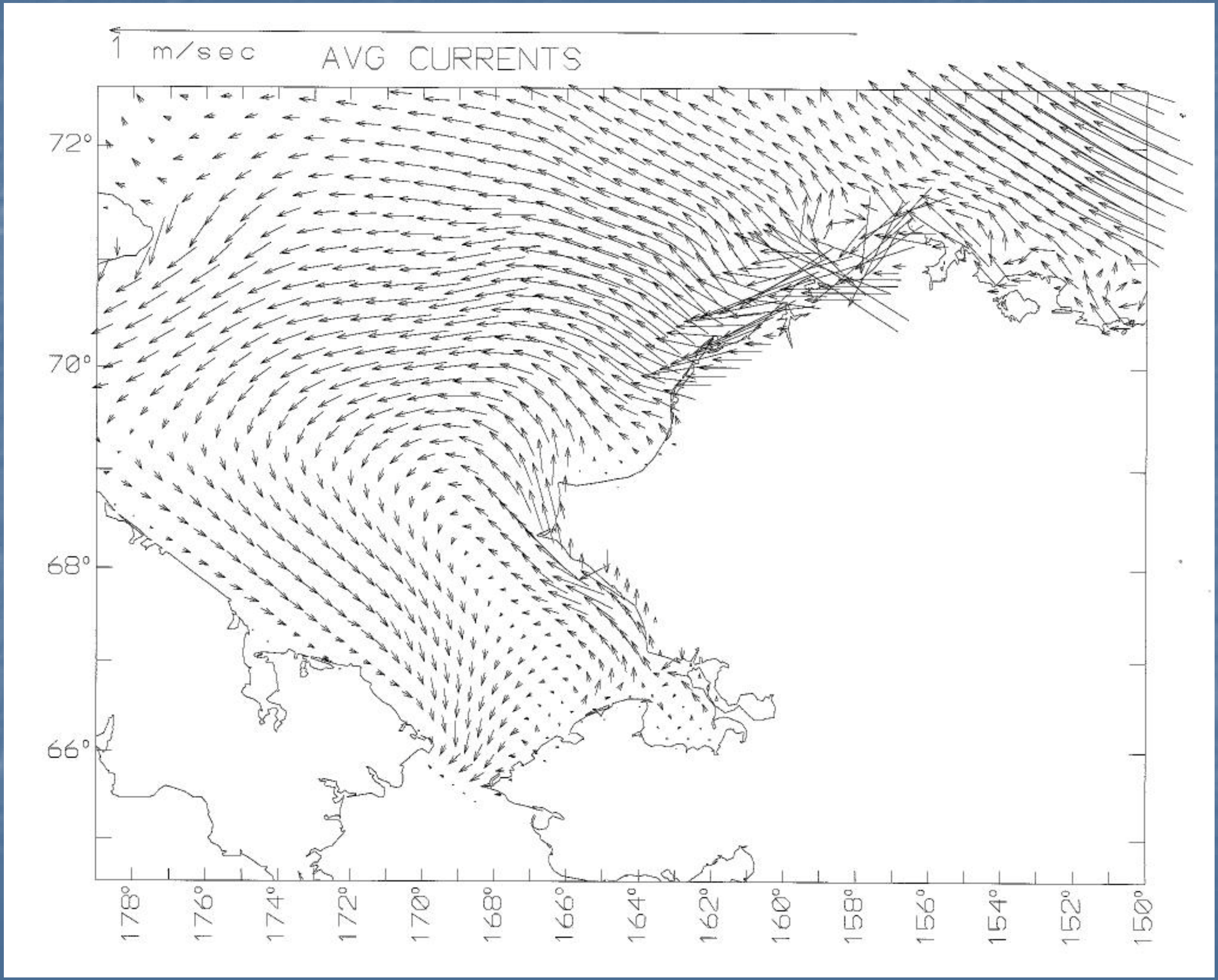
Trajectory Model
Oil Spill Risk Analysis

- Data required within the Study Area
  - Coastline, defined segments
  - At-sea resource definitions
  - Wind, grid of points
  - Ocean currents and sea-ice motion vectors from coupled ice/ocean model
  - Lease Sale locations, facilities, pipelines

Trajectory Model
Oil Spill Risk Analysis

- Wind
  - Satellite-based product, TOVS Pathfinder
- Landfast Ice Zone Mask, seasonal
- Ocean Currents – Ice Motion
  - Rutgers Coupled Ice/Ocean Model results
    - Daily intervals
    - Curvilinear grid

Oil Spill Risk Analysis



Oil Spill Risk Analysis Trajectory Analysis

- Simulate 2.7 million trajectories
  - 2700 from each hypothetical spill point
  - tabulate contacts to
    - Boundary segments
    - Environmental resource areas or
    - land segments.
- Special algorithm for oil in the moving pack ice, oil moves with the ice for concentration $\geq$80% ice.
- Results for different time intervals, 3-, 10-, 30-, 60-, 180-, and 360-days

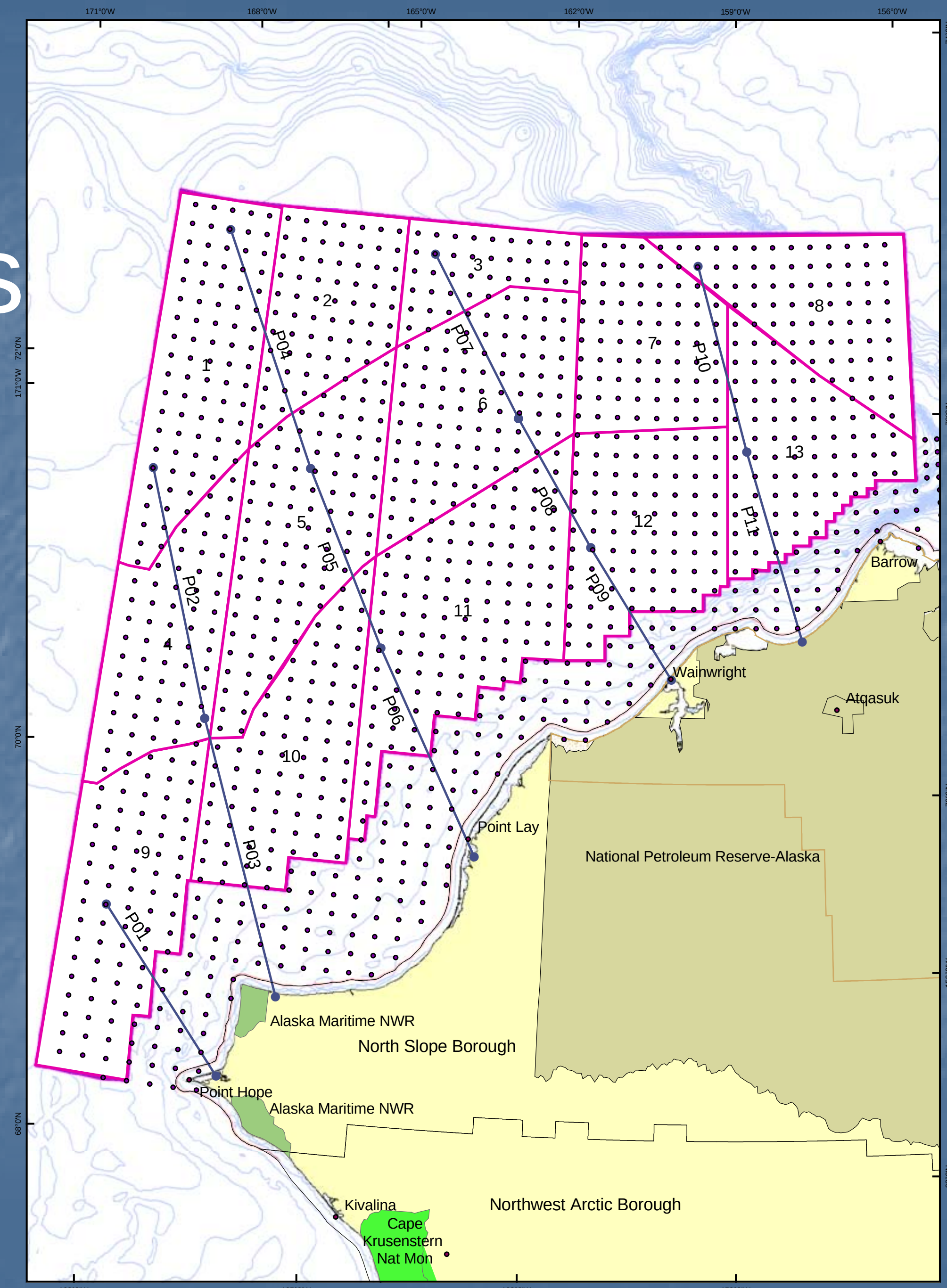
BOEMRE Trajectory Analysis

- OSRA is stochastic – probabilities are based on simulations of ice and ocean vectors generated by ocean circulation models and wind and spill occurrence records

- What OSRA is Not
  - It is not designed for use in “real time” or forecast mode
  - Real time spill predictions are driven by knowing what and where the spill occurred, winds and currents at time of spill, how spilled oil weathers

Hypothetical Platform Sites

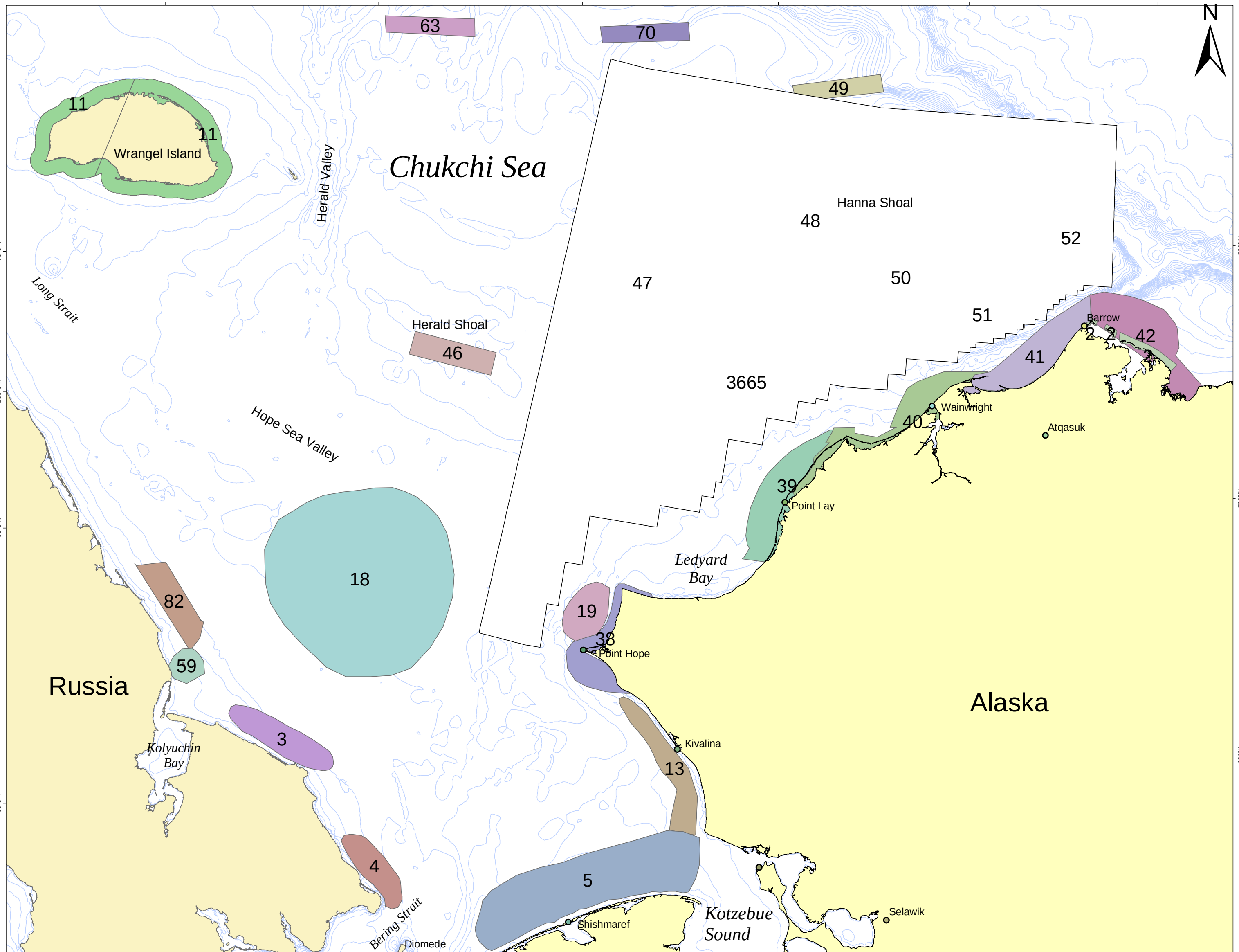
For Chukchi Sea there were 6148 lease blocks and 1002 hypothetical platform spill sites



Environmental Resource Areas

- Environmental Resources Areas are
  - Social, Economic Areas of Concern
  - Environmental Concern
  - Coastal Areas represented by Land Segments

Map A.1-2a Environmental Resource Areas Used in the Oil Spill Trajectory Analysis



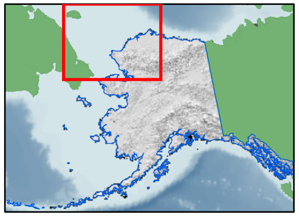
Legend

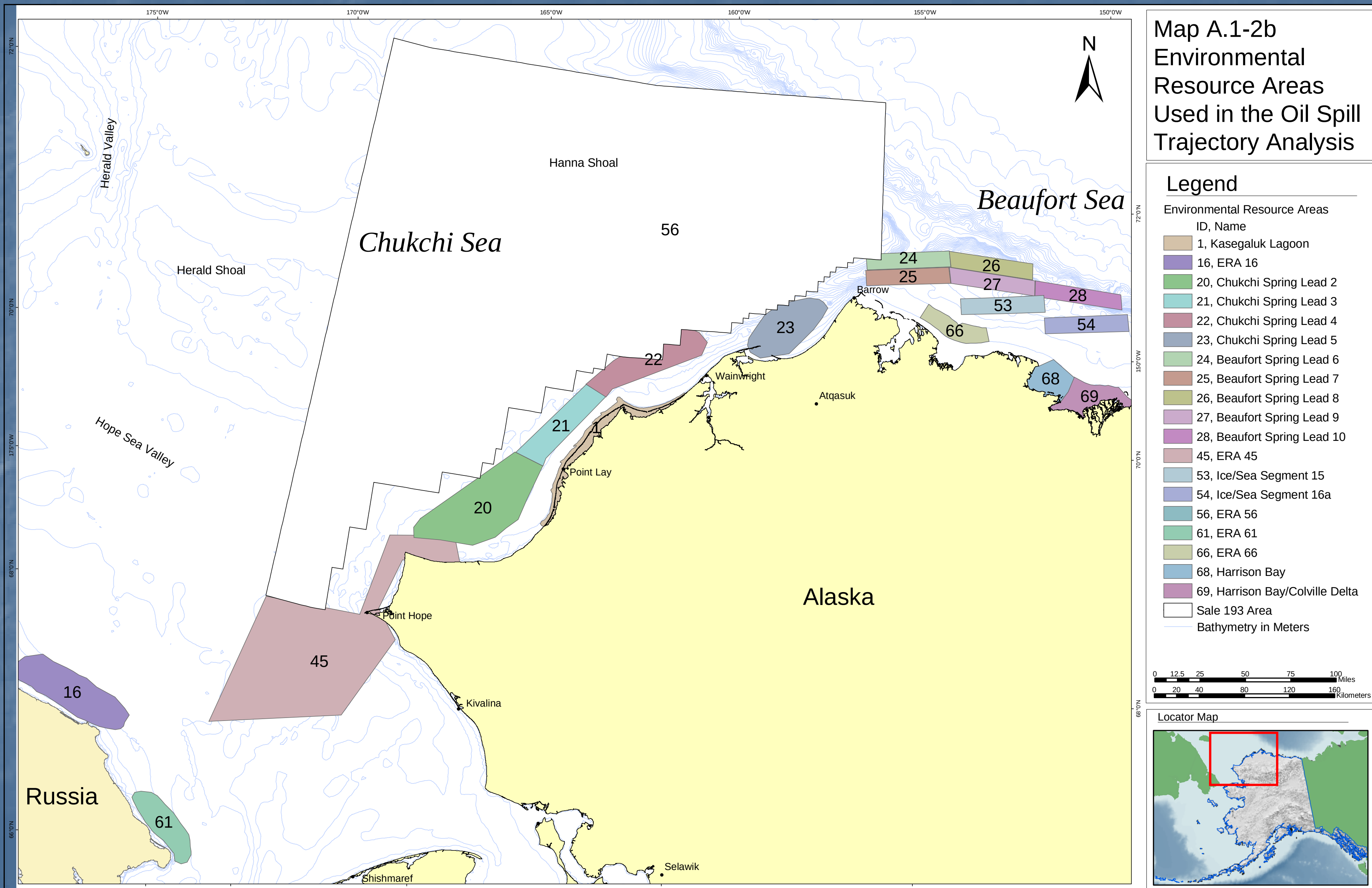
Environmental Resource Areas
ID, Name

- 2, Point Barrow, Plover Islands
- 3, ERA 3
- 4, ERA 4
- 5, ERA 5
- 11, Wrangel Island 12 nmi buffer
- 13, ERA 13
- 18, ERA 18
- 19, Chukchi Spring Lead 1
- 36, ERA 36
- 38, Point Hope Subsistence Area
- 39, Point Lay Subsistence Area
- 40, Wainright Subsistence Area
- 41, Barrow Subsistence Area 1
- 42, Barrow Subsistence Area 2
- 46, Herald Shoal Polynya
- 47, Ice/Sea Segment 10
- 48, Ice/Sea Segment 11
- 49, Hanna's Shoal Polynya
- 50, Ice/Sea Segment 12
- 51, Ice/Sea Segment 13
- 52, Ice/Sea Segment 14
- 59, ERA 59
- 63, ERA 63
- 65, ERA 65
- 70, ERA 70
- 82, ERA 82
- Sale 193 Area
- Bathymetry in Meters

Miles: 0, 15, 30, 60, 90, 120
Kilometers: 0, 20, 40, 80, 120, 160

Locator Map

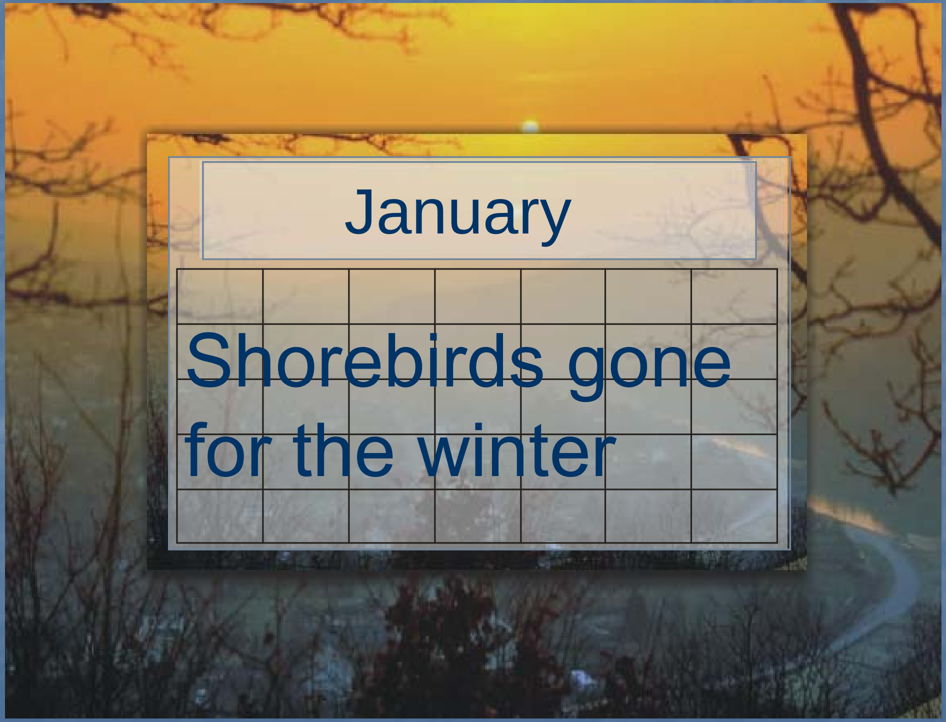




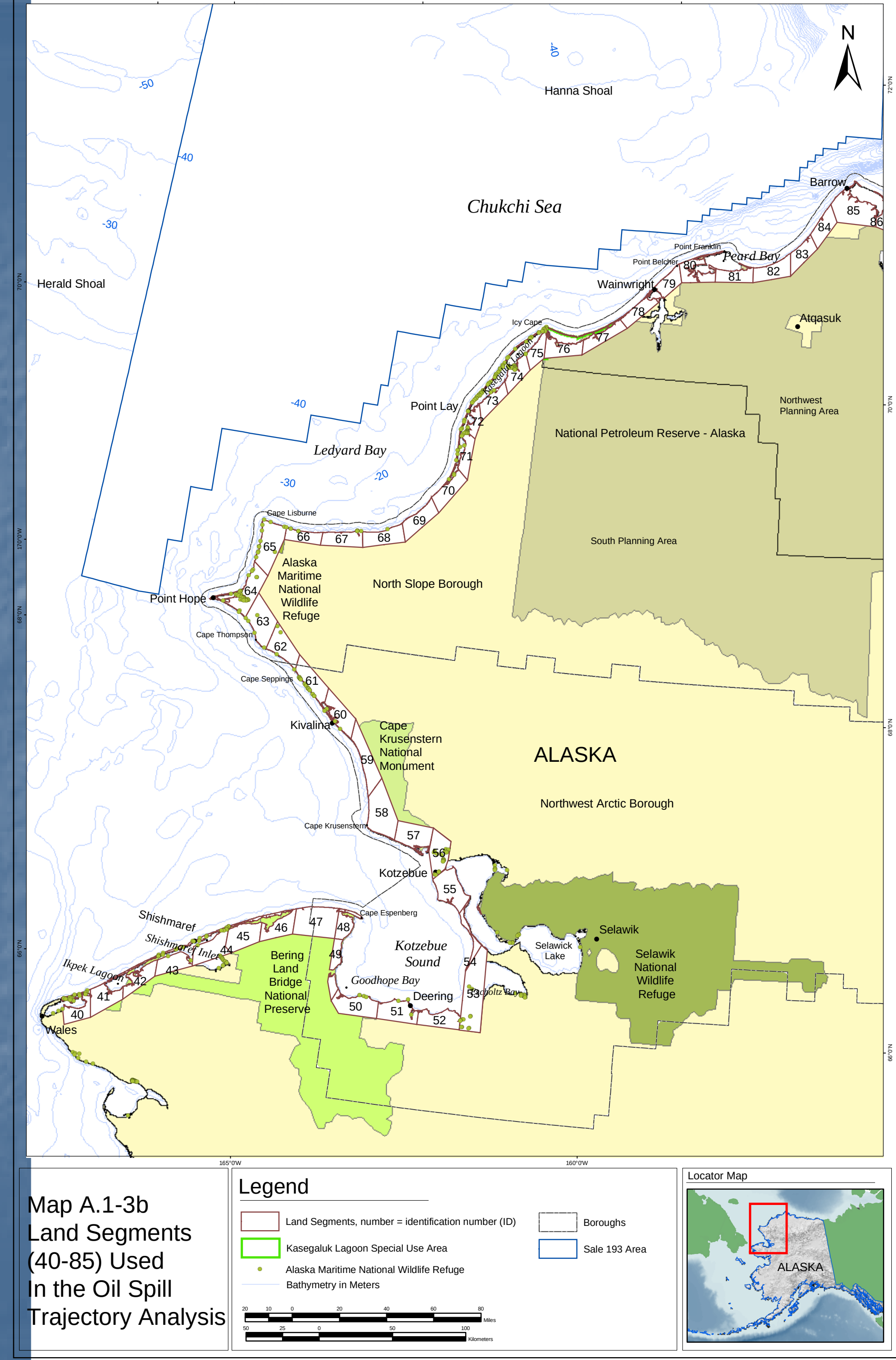
Map A.1-2b Environmental Resource Areas Used in the Oil Spill Trajectory Analysis
Legend
Environmental Resource Areas
ID, Name
1, Kasegaluk Lagoon
16, ERA 16
20, Chukchi Spring Lead 2
21, Chukchi Spring Lead 3
22, Chukchi Spring Lead 4
23, Chukchi Spring Lead 5
24, Beaufort Spring Lead 6
25, Beaufort Spring Lead 7
26, Beaufort Spring Lead 8
27, Beaufort Spring Lead 9
28, Beaufort Spring Lead 10
45, ERA 45
53, Ice/Sea Segment 15
54, Ice/Sea Segment 16a
56, ERA 56
61, ERA 61
66, ERA 66
68, Harrison Bay
69, Harrison Bay/Colville Delta
Sale 193 Area
Bathymetry in Meters
0 12.5 25 50 75 100 Miles
0 20 40 80 120 160 Kilometers
Locator Map
N
Chukchi Sea
Beaufort Sea
Hanna Shoal
Herald Shoal
Herald Valley
Hope Sea Valley
Alaska
Russia
Barrow
Wainwright
Atqasuk
Point Lay
Point Hope
Kivalina
Shishmaref
Selawik
56
24
25
26
27
28
53
54
66
23
22
21
1
20
45
16
61
68
69
175°0'W
170°0'W
165°0'W
160°0'W
155°0'W
150°0'W

Seasonal Vulnerability

Vulnerability of a single Environmental Resource Area may vary according to time of year.



Land Segments 40-85



Oil Spill Risk Analysis Conditional Probability

- A conditional probability relates the hypothetical spill location to the Environmental Resource or land segment.
- It is a “source mode” analysis, focused on the spill location and tabulates which resources and land segments may be contacted.
- The Conditional Probabilities are utilized in the Oil Spill Response Plan documents. The spill locations may be formulated differently than the Lease Sale areas.

Conditional Probability Table

Annual Probabilities, Contacts up to 360 Days

Segment	LA09	LA10	LA11	LA12	LA13
76	-	1	1	-	-
77	-	1	1	1	-
78	-	1	2	3	-
79	-	1	2	4	1
80	-	1	2	5	2
81	-	1	1	3	1
82	-	-	1	3	2
83	-	-	1	2	2
84	-	-	-	2	5
85	-	-	-	3	10

Oil Spill Risk Analysis Combined Probability

- A combined probability deals with two or more random variables.
- For the oil-spill risk analysis the two variables are:
  - the probability of a spill occurring
  - the probability of a spill contacting
- The two variables are multiplied to estimate the mean number of spills that will both occur and contact environmental resource areas or land segments.

Combined Probability Calculation

CALCULATION OF COMBINED PROBABILITIES

[CONDITIONAL PROBABILITY MATRIX] X [SPILL OCCURRENCE MATRIX] = [UNIT RISK MATRIX]

[UNIT RISK MATRIX] X [VOLUME VECTOR (BBBL)] = [ESTIMATED MEAN NUMBER OF SPILLS]

POISSON DISTRIBUTION ([ESTIMATED MEAN NUMBER OF SPILLS]) = [ESTIMATED PROBABILITY OF ONE OR MORE SPILLS]

Proposed Action, Combined Probability, Spills ≥ 1,000 Bbls

Environmental Resource	60 day %	60 day Mean #	360 day %	360 day Mean #
Land	9	0.10	14	0.15
Kasegaluk Lagoon	3	0.03	4	0.04
Point Barrow/Plover Island	0	0.00	1	0.01
ERA 6	4	0.04	6	0.06
Ledyard Bay Critical Eider Hab	8	0.08	8	0.09
ERA18	3	0.03	3	0.03
Chukchi Spring Lead 1	0	0.00	0	0.00
Chukchi Spring Lead 2	2	0.02	2	0.02
Chukchi Spring Lead 3	2	0.02	2	0.02
Chukchi Spring Lead 4	2	0.02	3	0.03
Chukchi Spring Lead 5	0	0.00	1	0.01
ERA 56	3	0.03	4	0.04

Summary
Combined Probability

- A combined probability relates the Lease Sale Federal Action to the Environmental Resource.
- It is a “receptor mode” analysis, focused on the resource and not the spill location.
- The EIS subject matter experts use the Combined Probability to describe the impact on resources.


U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Beaufort/Chukchi Seas Surface Wind Climatology, Variability, and Extremes: Data Analysis and Model Simulation

Xiangdong Zhang[1], Jing Zhang[2], Jeremy Krieger[3], Steve Stegall[2], Fuhong Liu[2], Wei Tao[1], Paula Moreira[1], and Martha Shulski[4]

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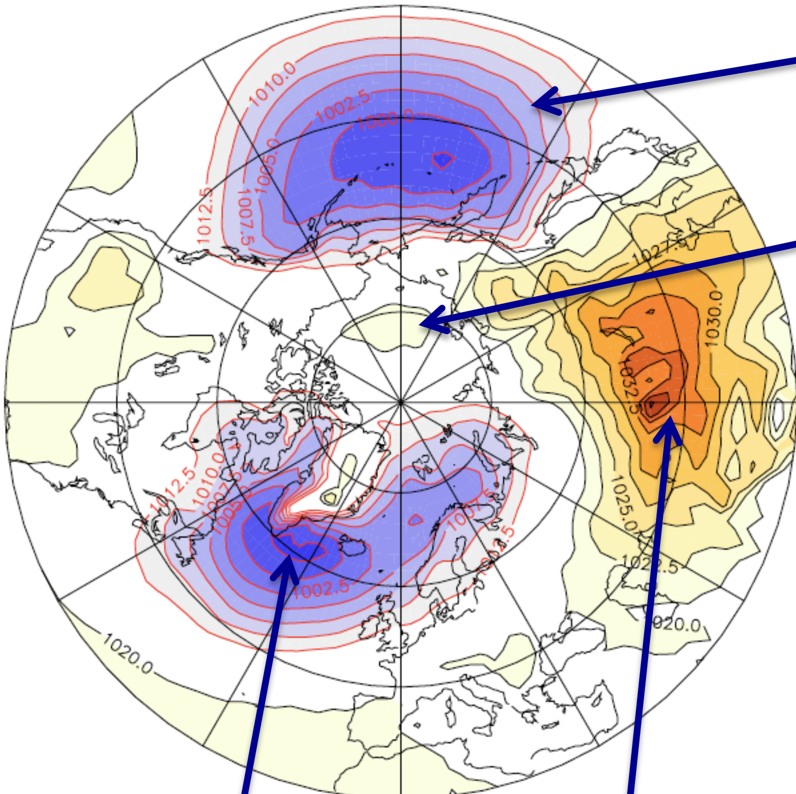
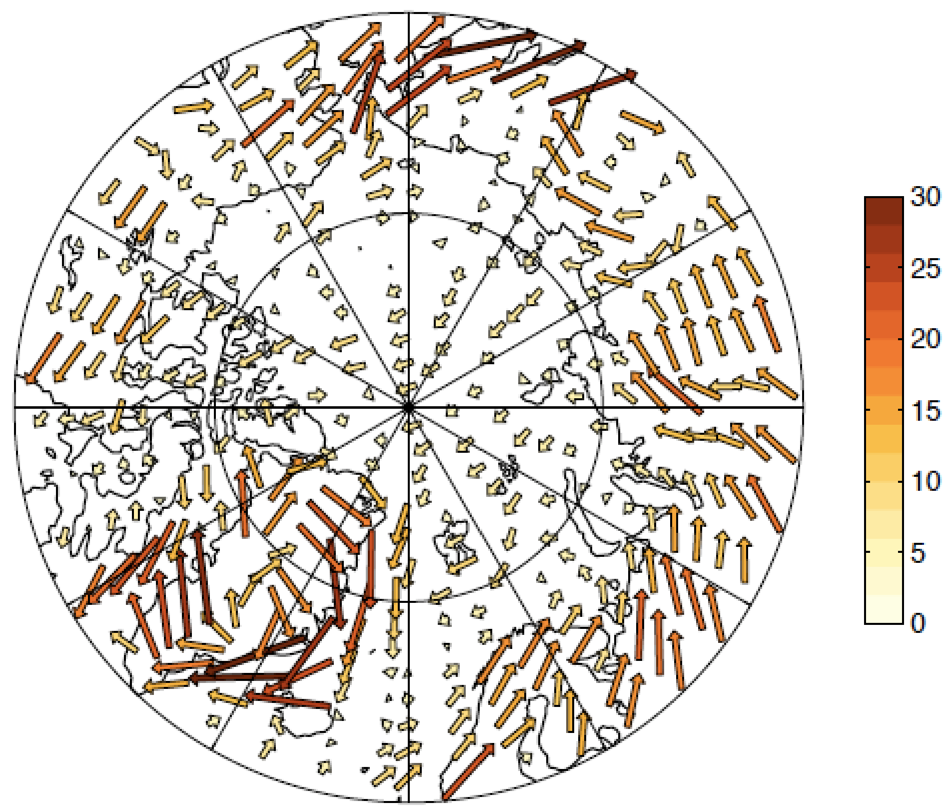
[4]High Plains Regional Climate Center, University of Nebraska-Lincoln

Outlines

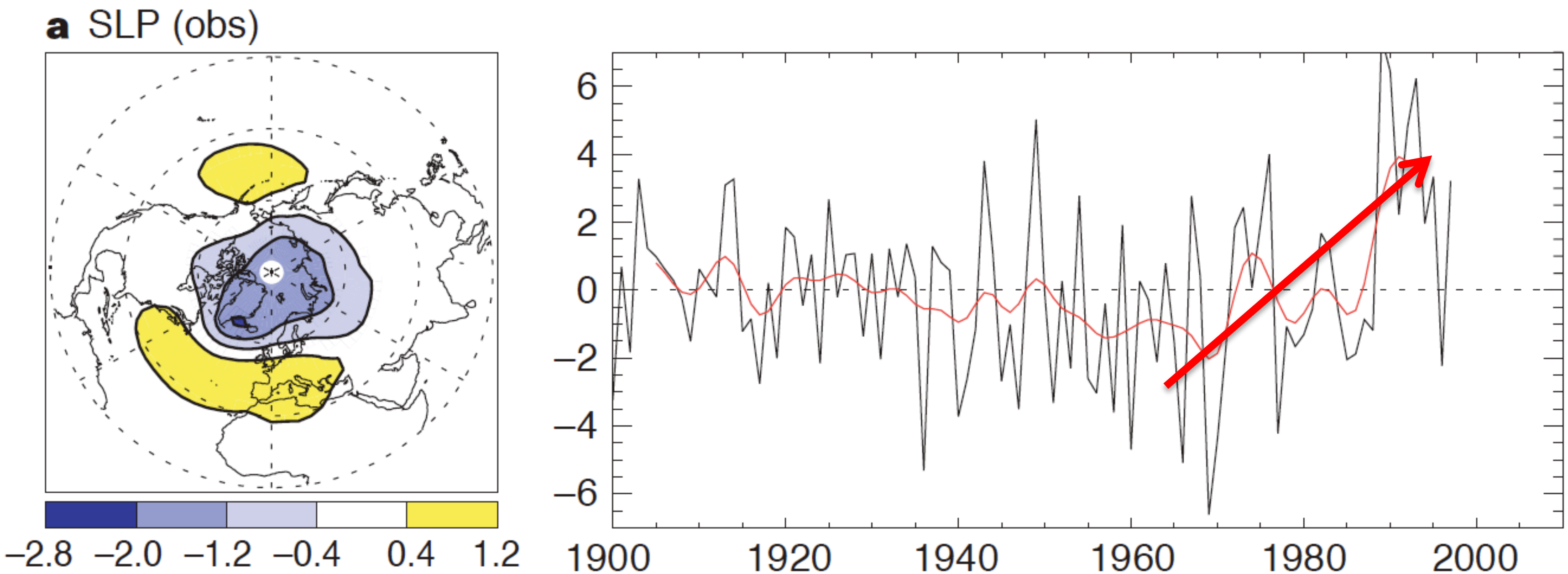
- Large scale atmospheric circulation's control
  - ➢ leading model explains ~ 20-25% of variance
  - ➢ provide IC/BC to regional/mesoscale models
- Regional and finer scale features
  - ➢ highly variable wind speed and direction
  - ➢ local dynamic and thermodynamic effects
- Mesoscale modeling and data assimilation
  - ➢ Develop realistic, high resolution data
  - ➢ Understand regional variability and change

- **Climatology of surface atmospheric circulation: sea level pressure and surface wind stress**

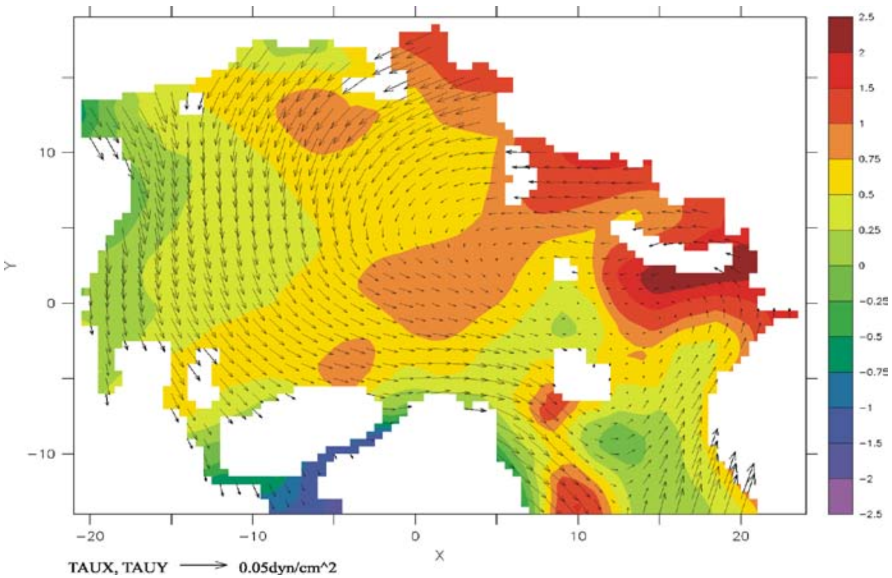




- **Arctic Oscillation shows a large interannual fluctuations and an upward trend from 1970s to 1900s.**

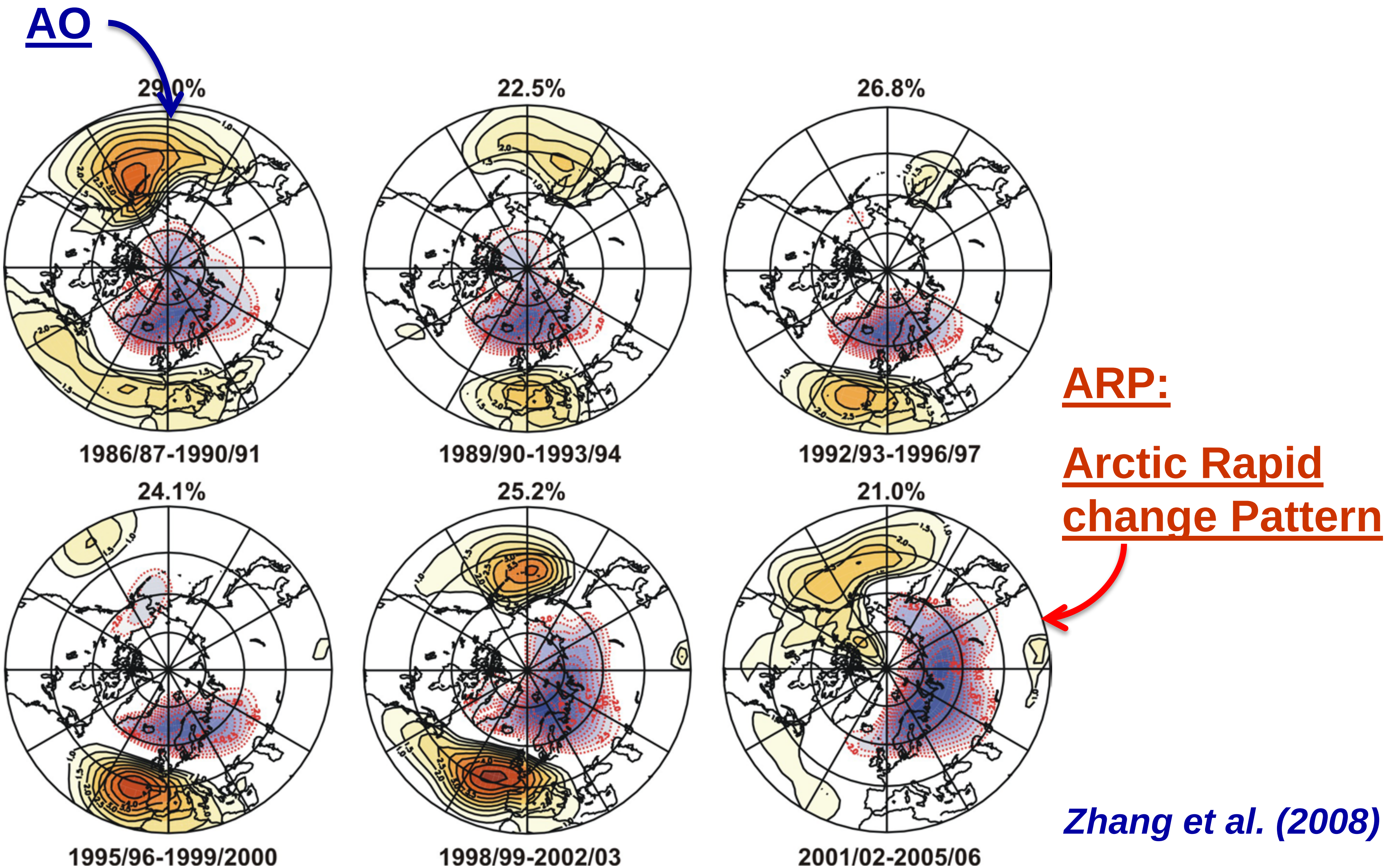


Thompson and Wallace (1998)



Zhang et al. (2003)

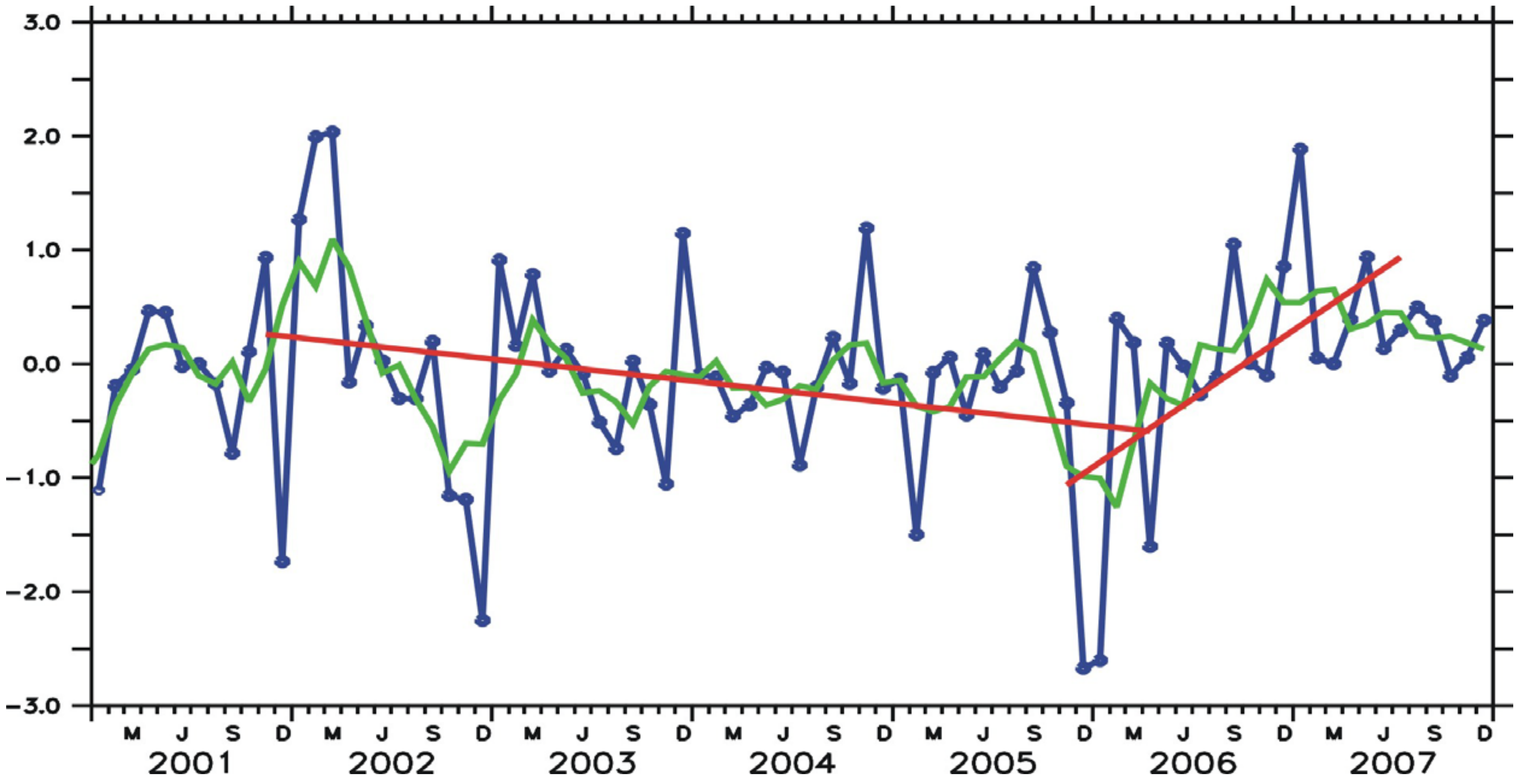
- **Atmospheric circulation pattern has radically shifted and rapid systematic changes occurred since late 1990s.**



Zhang et al. (2008)

- **ARP was negatively polarized before 2006 and then swiftly changed its phase, impacting wind, sea ice and ocean**

ARP Index (All Months Included)

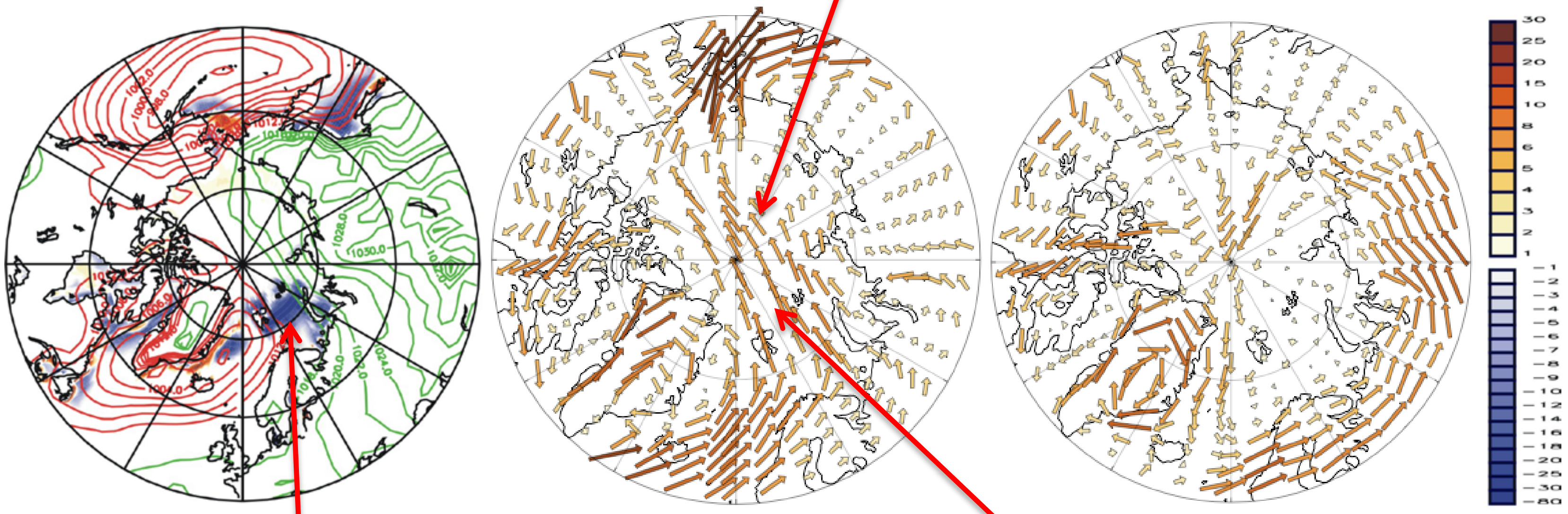


Zhang et al. (2008)

- **ARP steered surface wind and its polarity and swift phase transition caused extreme sea ice loss in summer 2007.**

✓The ARP phase change reversed wind pattern and reduced sea ice cover
✓The ARP phase change enhanced Pacific warm air and warm water inflow
✓The enlarged open water enhance albedo feedback

Composite Analyses of SIC and SLP Based on ARP Index



Negative ARP (mainly in winter) Before 2006

Positive ARP (mainly in summer) After 2006

Differences in SLP

The ARP associated atmospheric and oceanic heat transport reduced sea ice and enlarged open water

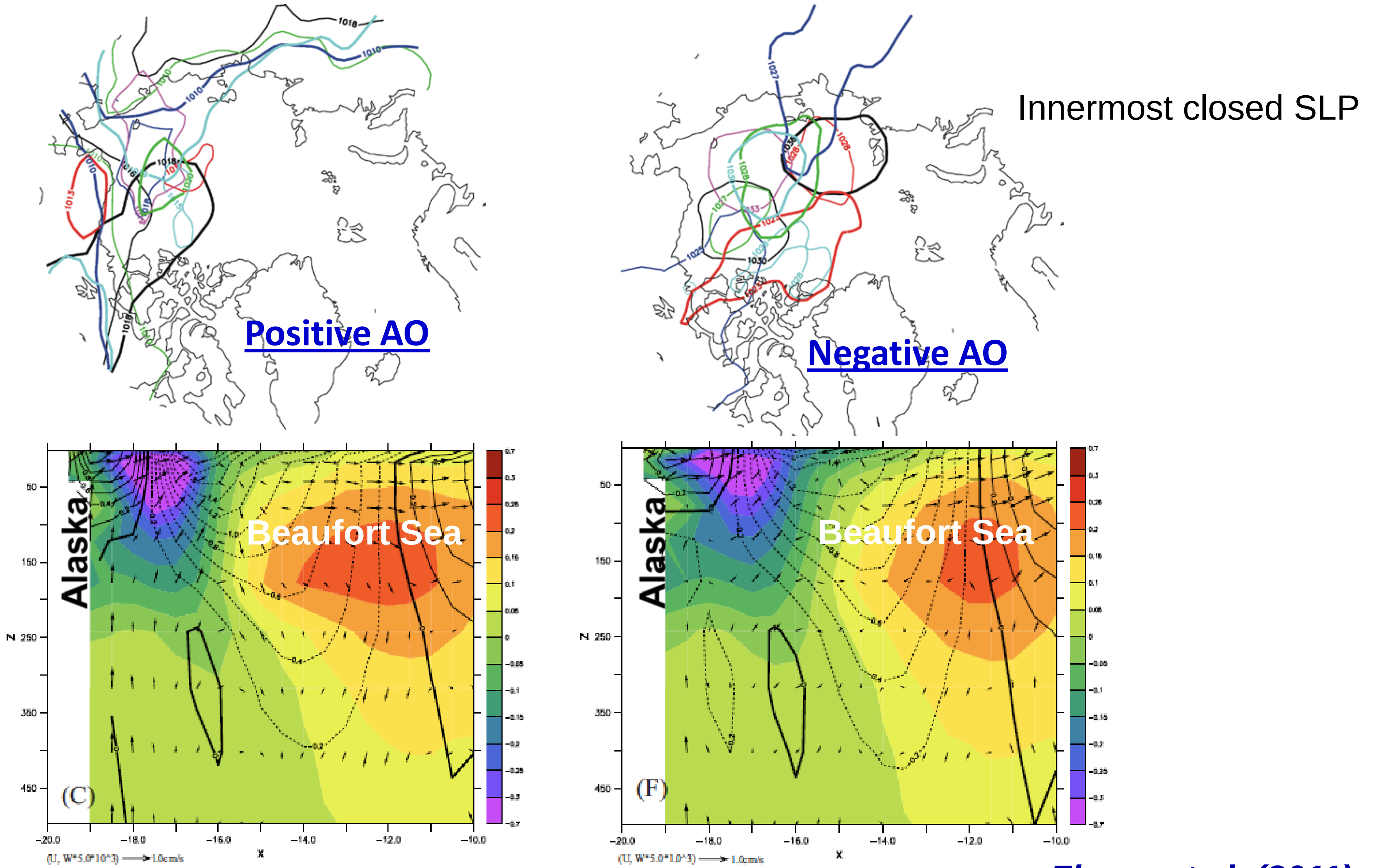
✓The previously warmed ocean retains the decreased sea ice
✓The enlarged open water enhance albedo feedback

Large scale atmospheric circulation plays an important steering role in surface wind field and then impacts underlying sea ice and ocean.

However,

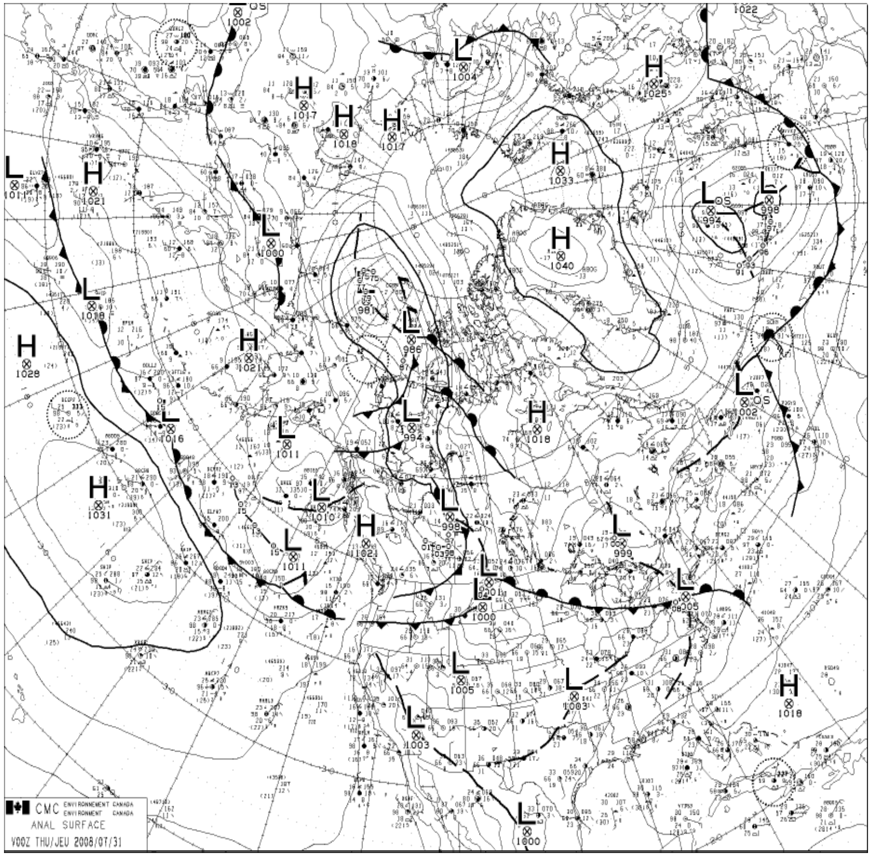
surface wind has its own complex regional features, and influences local as well as large scale sea ice and ocean processes.

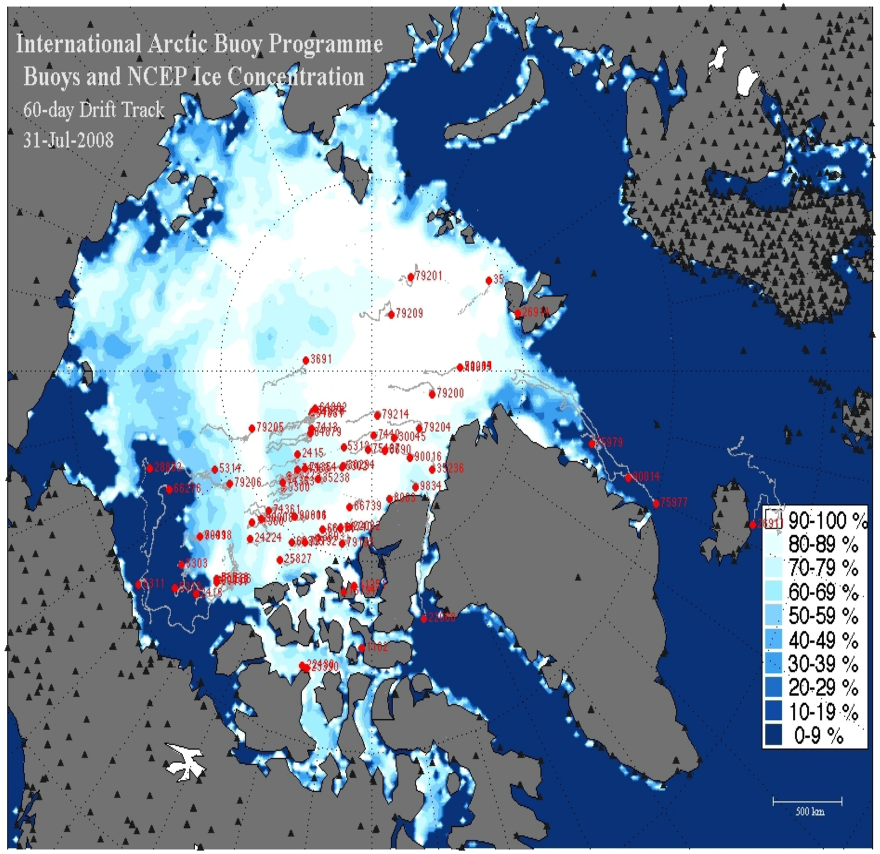
- **The Beaufort High relocates regionally and strengthens/ weakens with AO, impacting regional ocean process.**



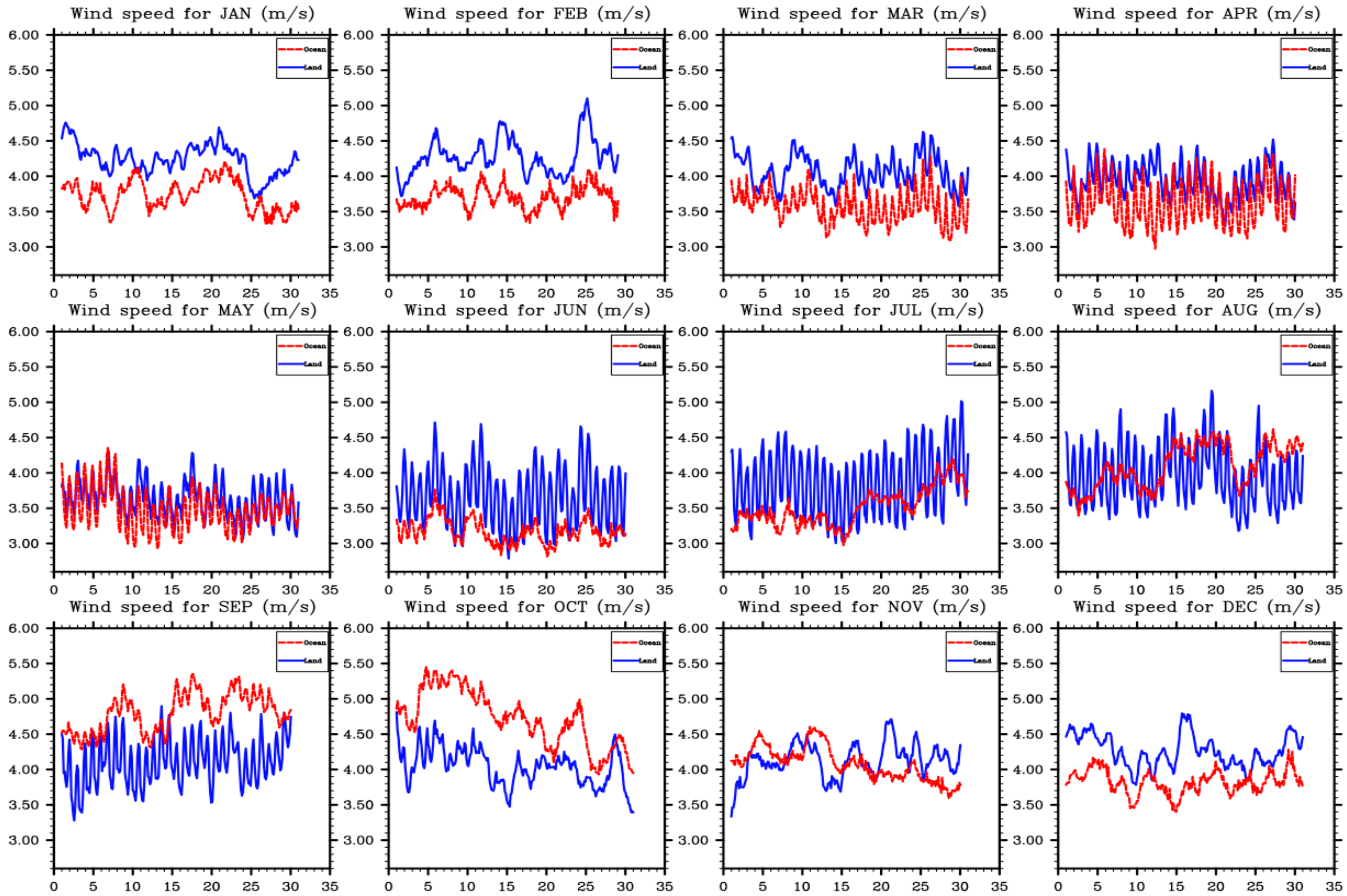
Zhang et al. (2011)

- **Single synoptic scale weather system can cause highly variable surface wind field and impact sea ice.**

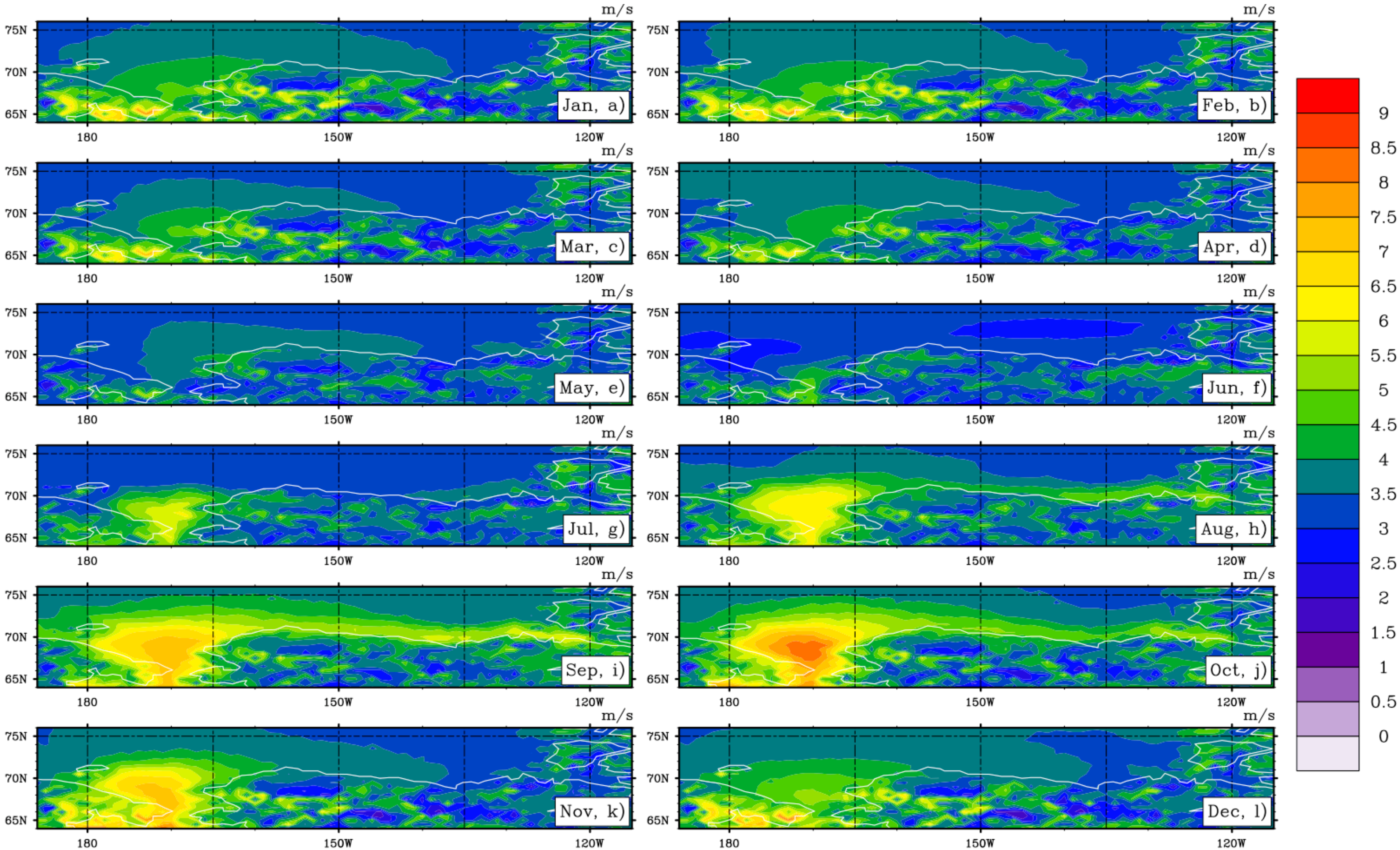




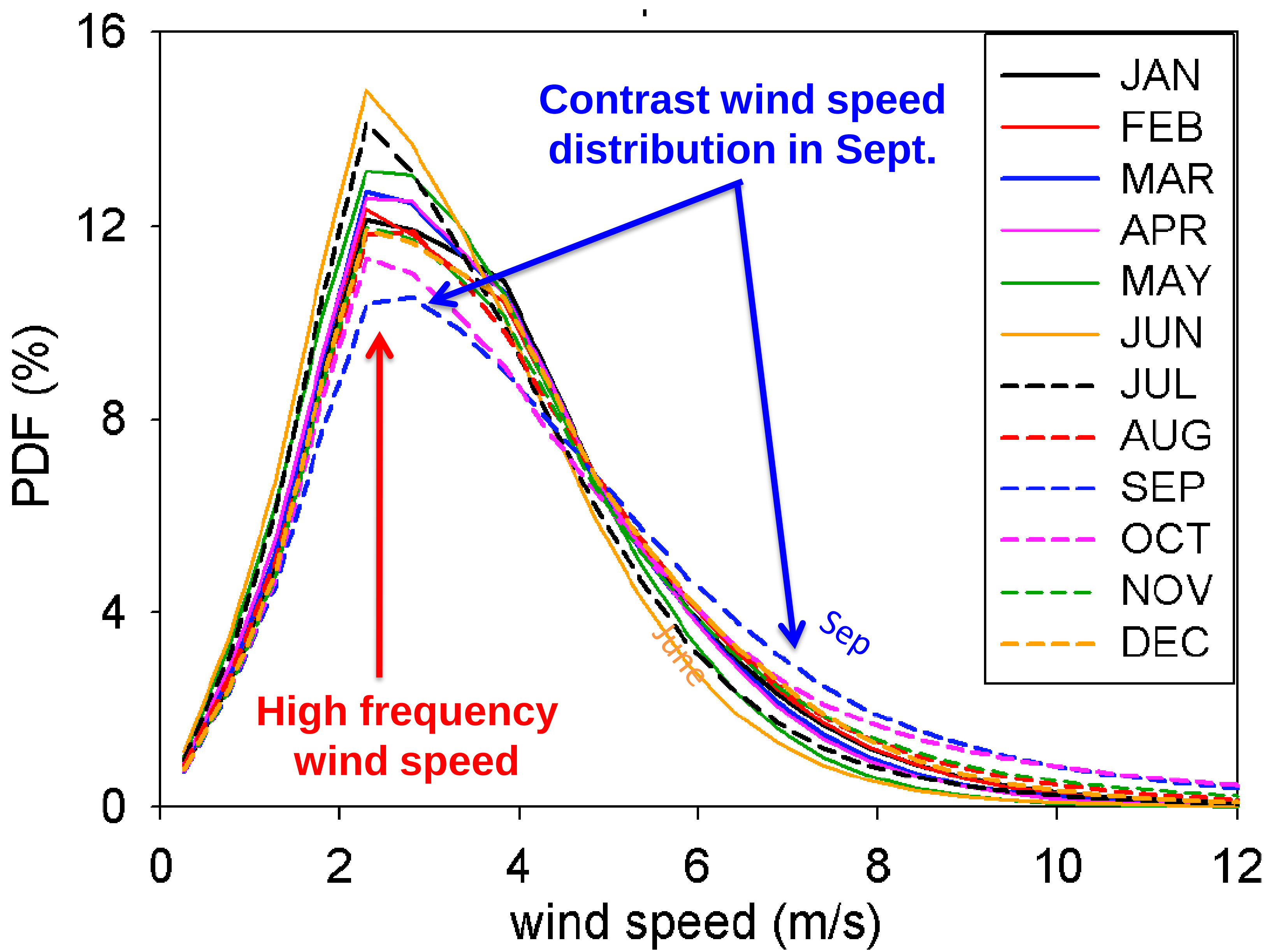
- **High frequency variability and large diurnal cycle occur in spring for ocean (red) and summer for land (blue) (NARR).**



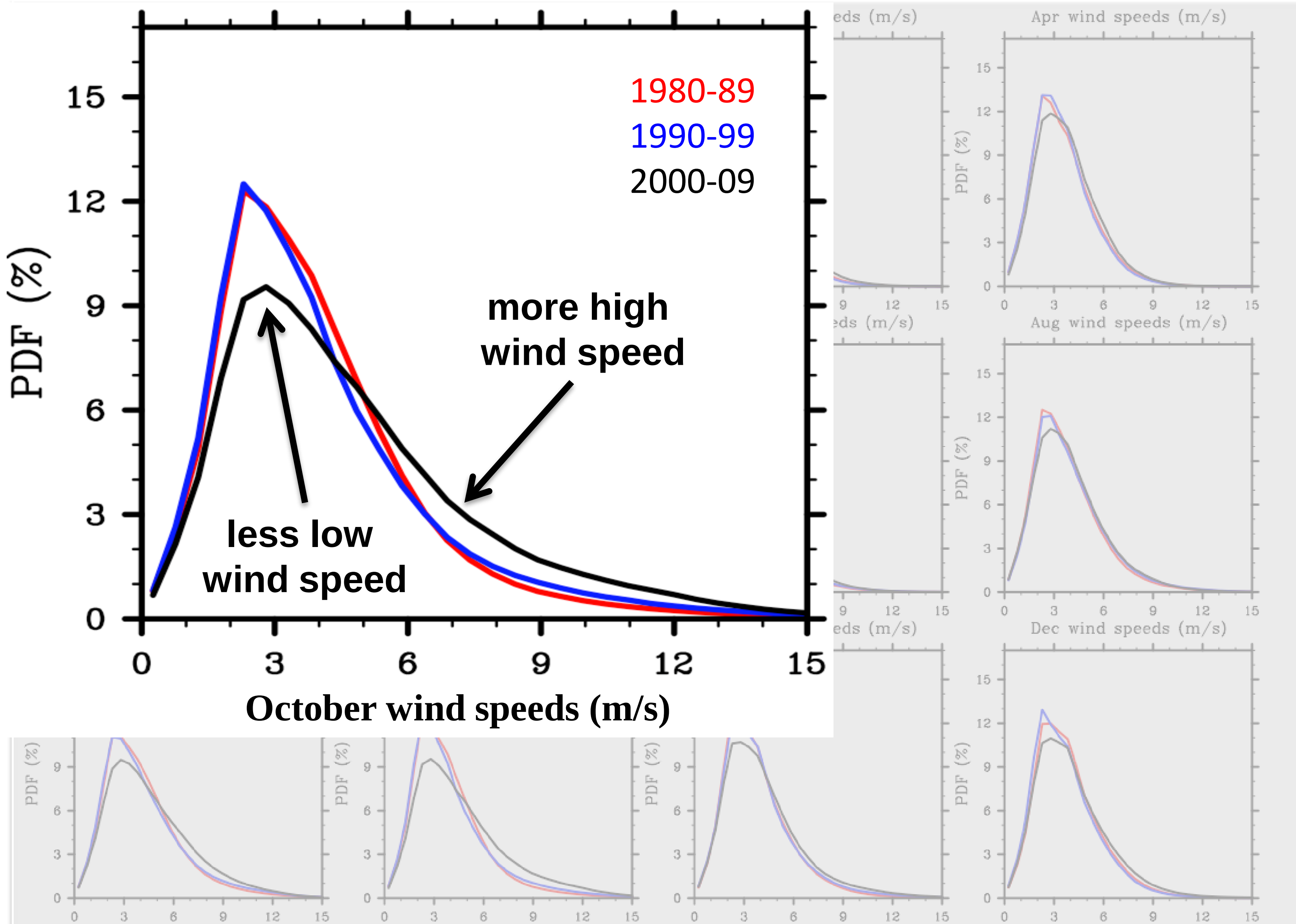
▪ Surface wind speed analysis (including high frequency variability): Monthly climatology from 1979-2009 (NARR).



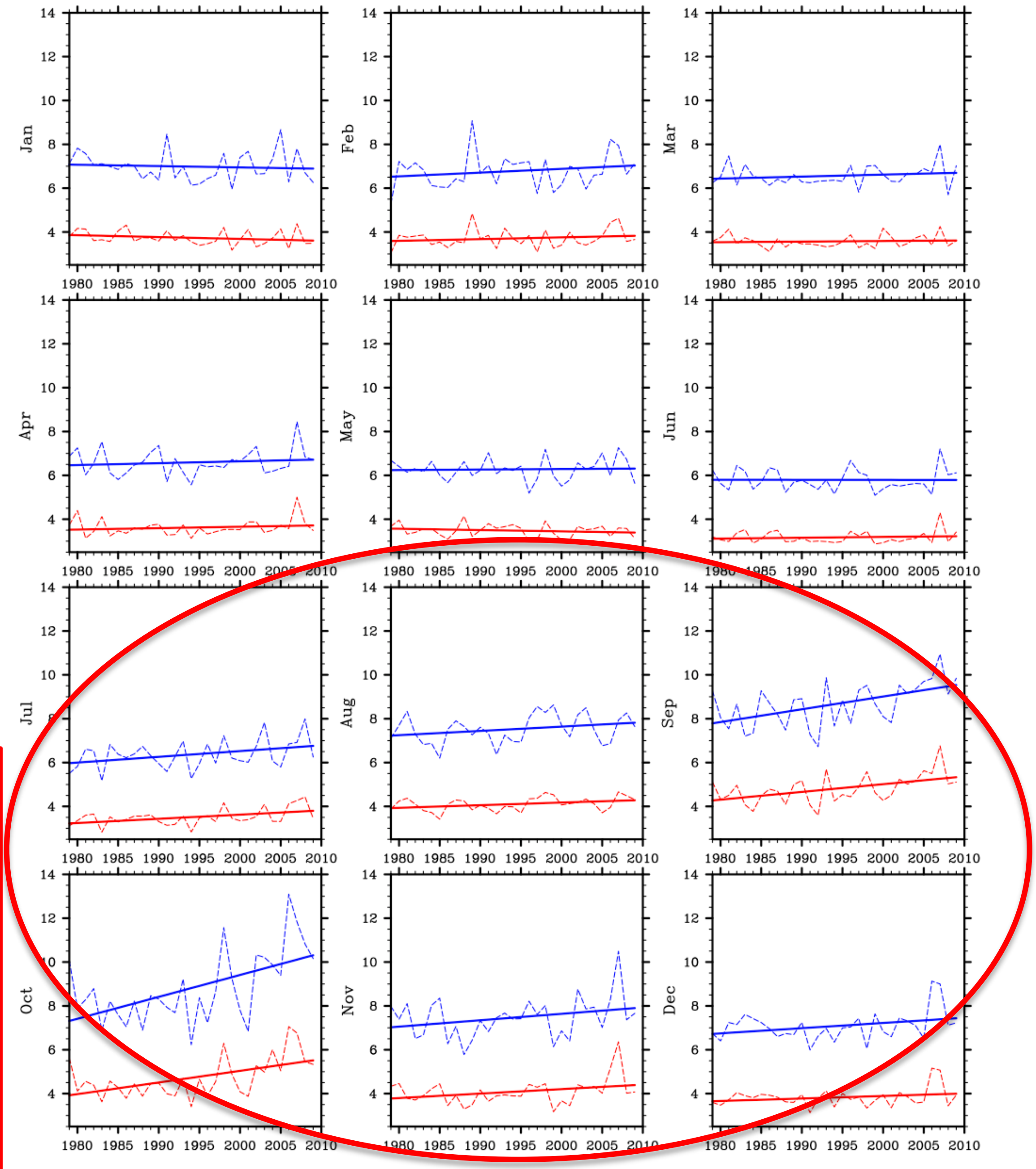
- **Regional mean surface wind speed: High frequency and the largest seasonal cycle occur between 2-4 m/s (NARR).**



▪ **The PDF in 3 decades and the large differences occur in Sept – Oct (NARR).**



- **Monthly mean (red) and extreme (blue, 95th percentile) wind speed have increased in the second half of the year.**

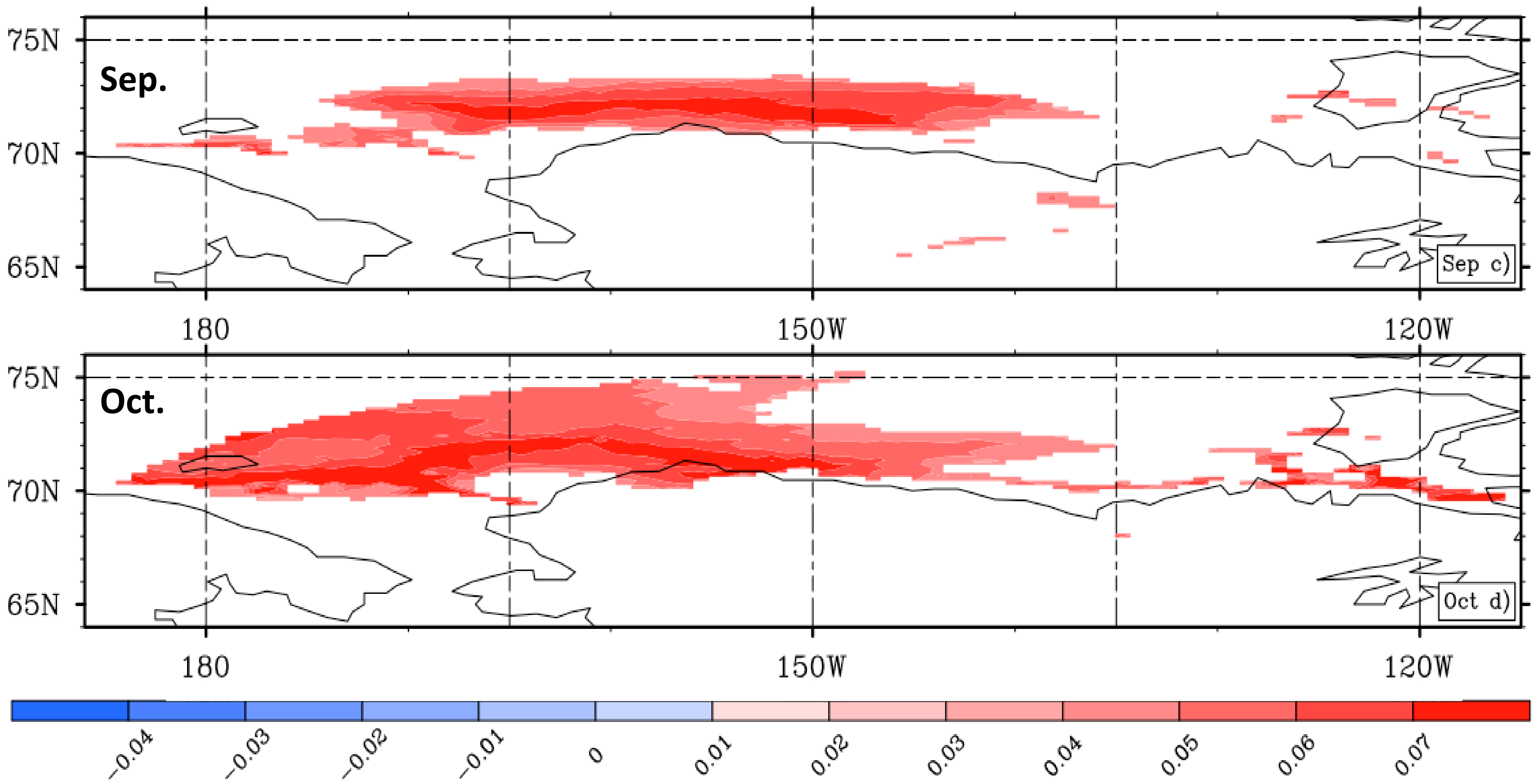


The largest increase occurs in Oct:

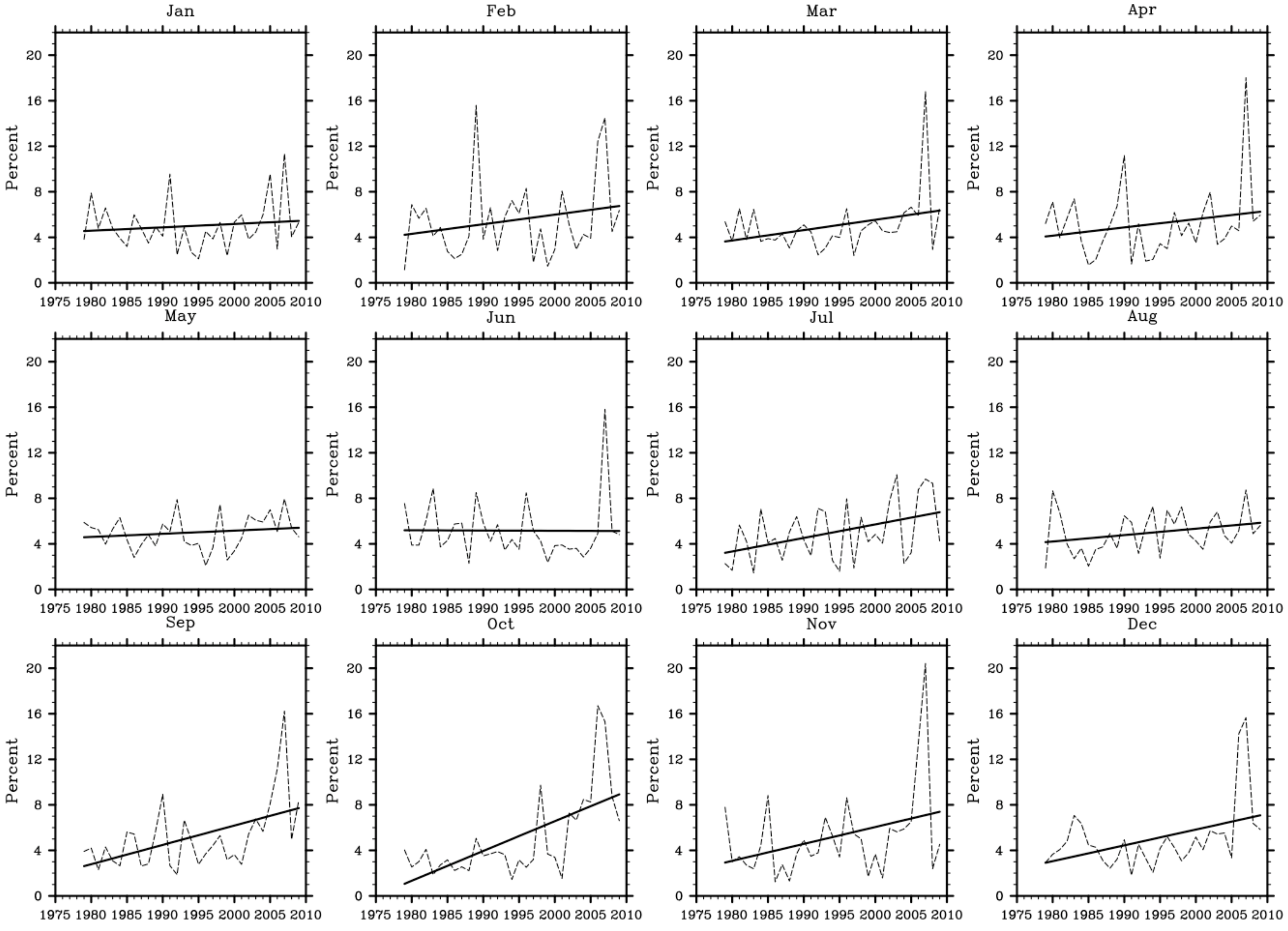
The trend of mean wind speed: 0.5 m/s per decade

The trend of extreme wind speed: 1.0 m/s per decade

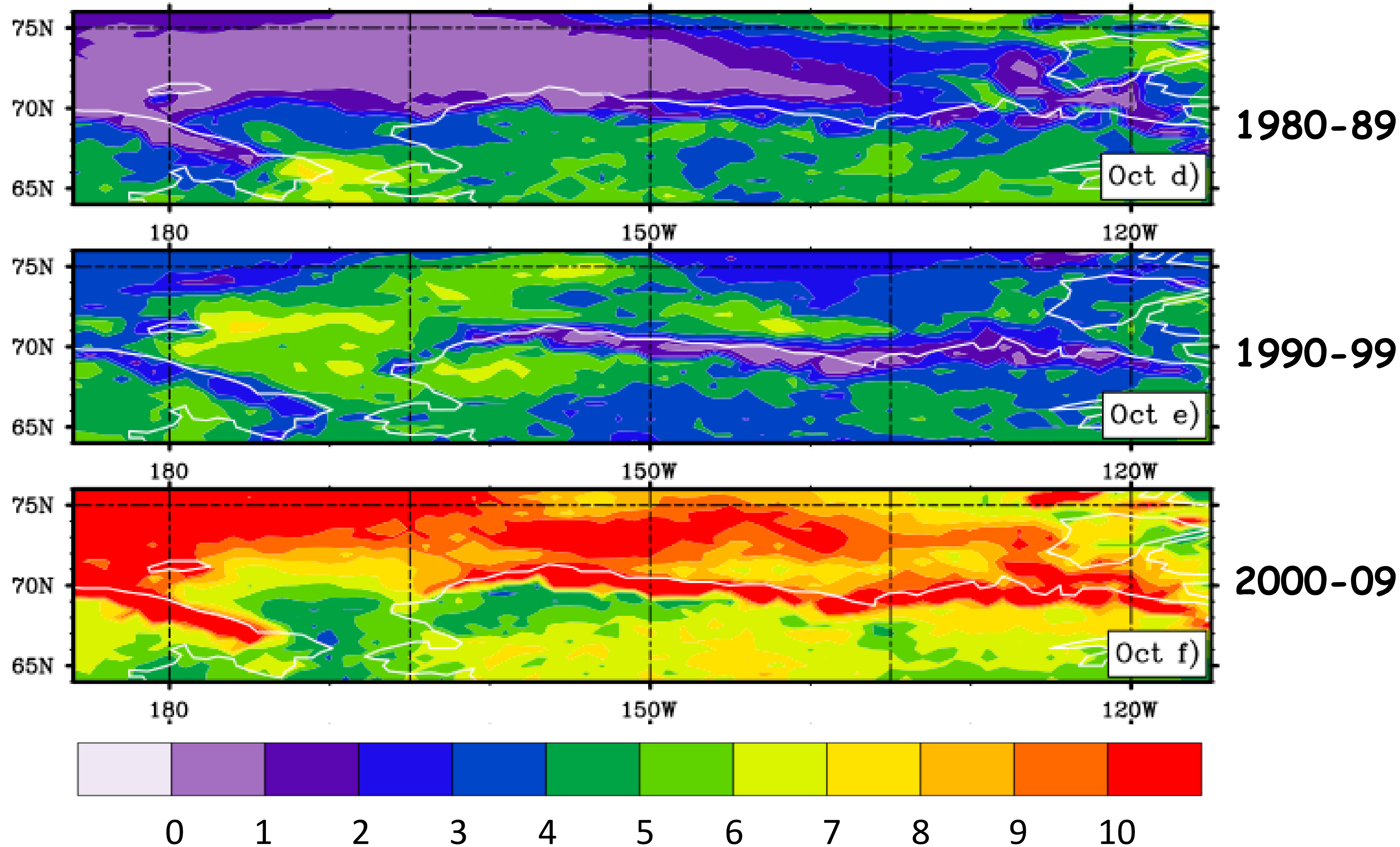
- **Spatial distribution of the monthly mean wind speed trend in Sept and Oct (95% significance, NARR).**



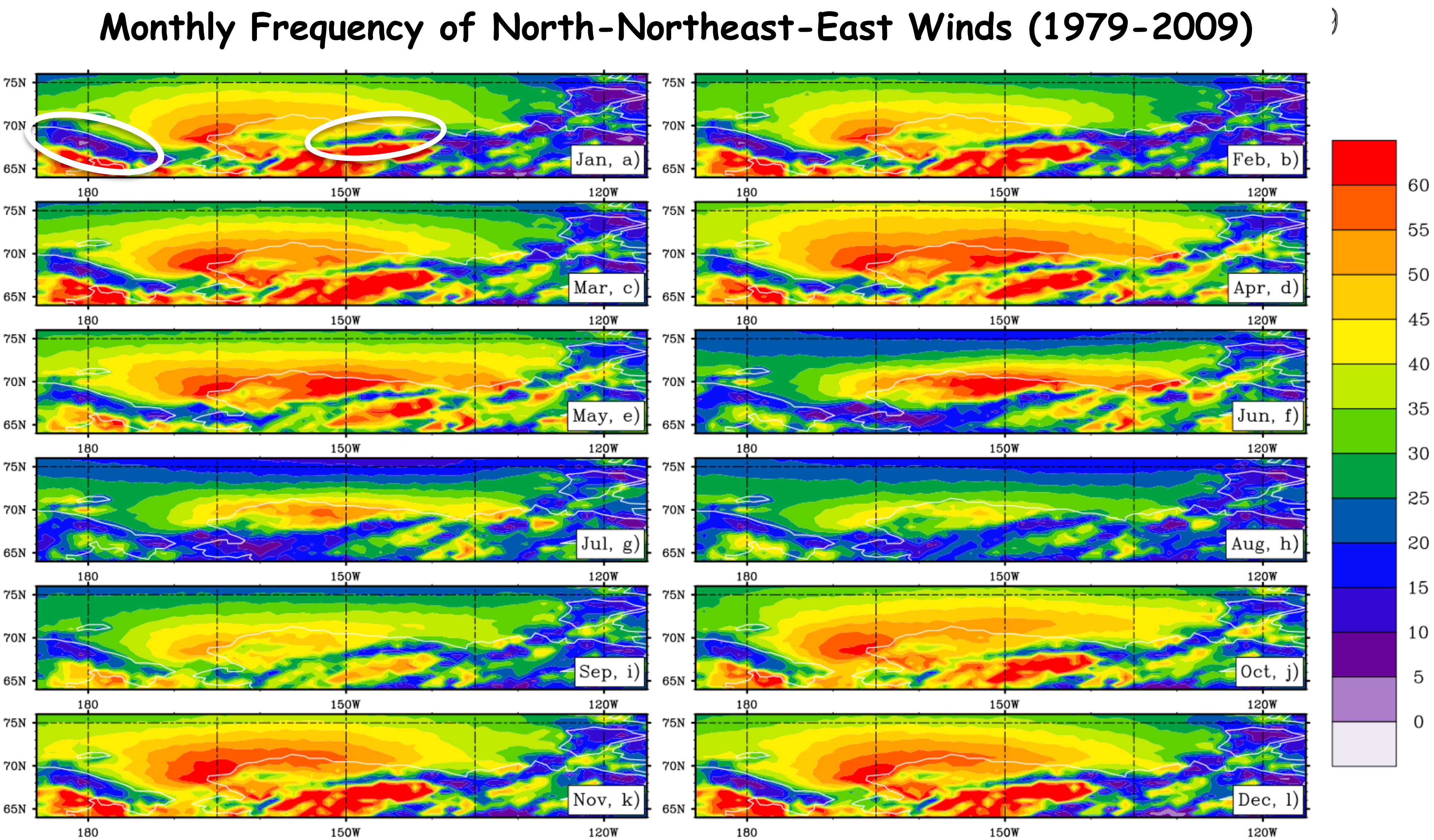
- **The monthly frequency of extreme wind speed has been increased, in particular in Sept – Nov (NARR).**



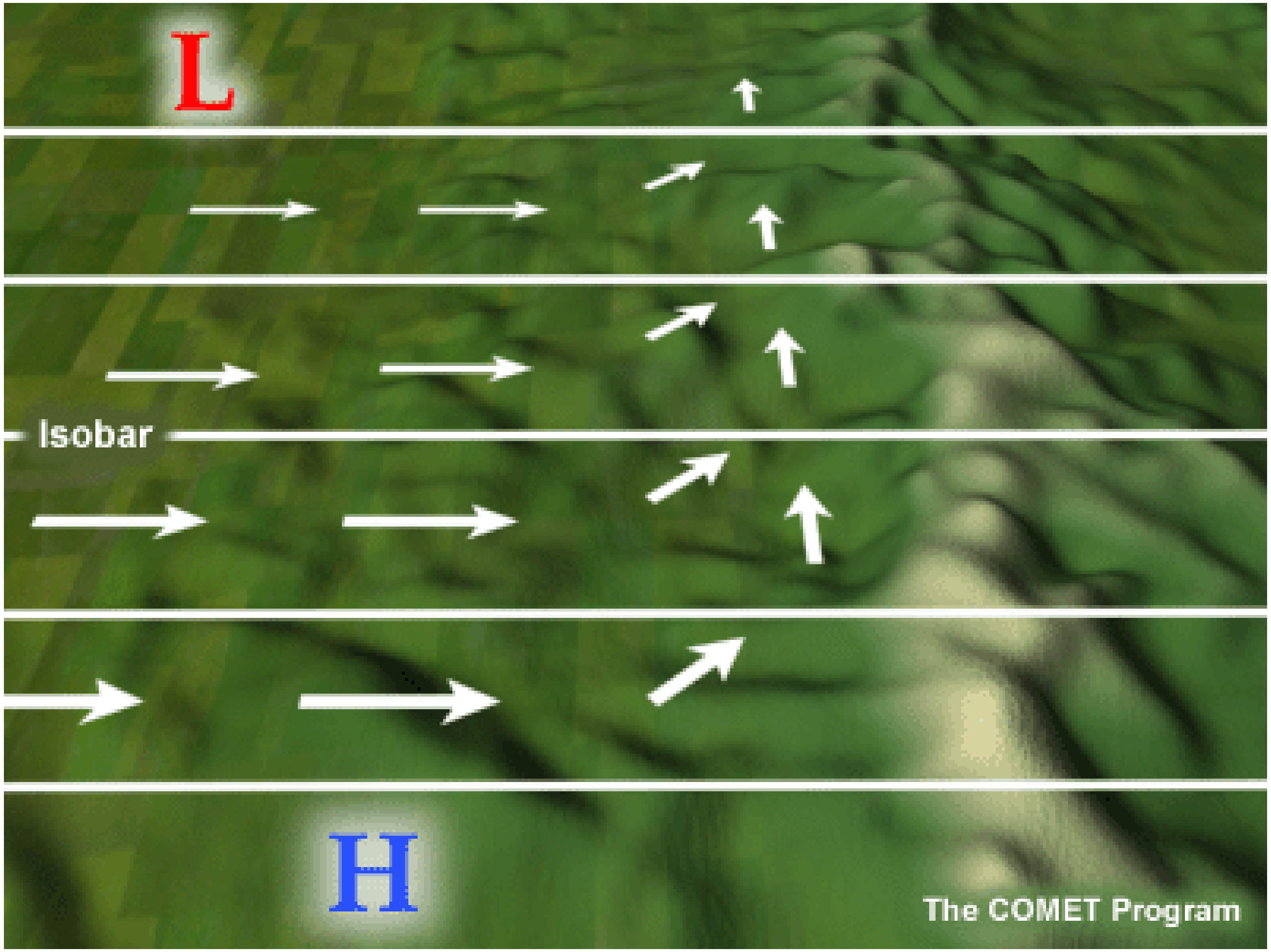
- **Spatial distribution of the frequency of extreme wind speed in Oct in the 3 decades (NARR).**



▪ Mesoscale features: Mountain barrier effect.

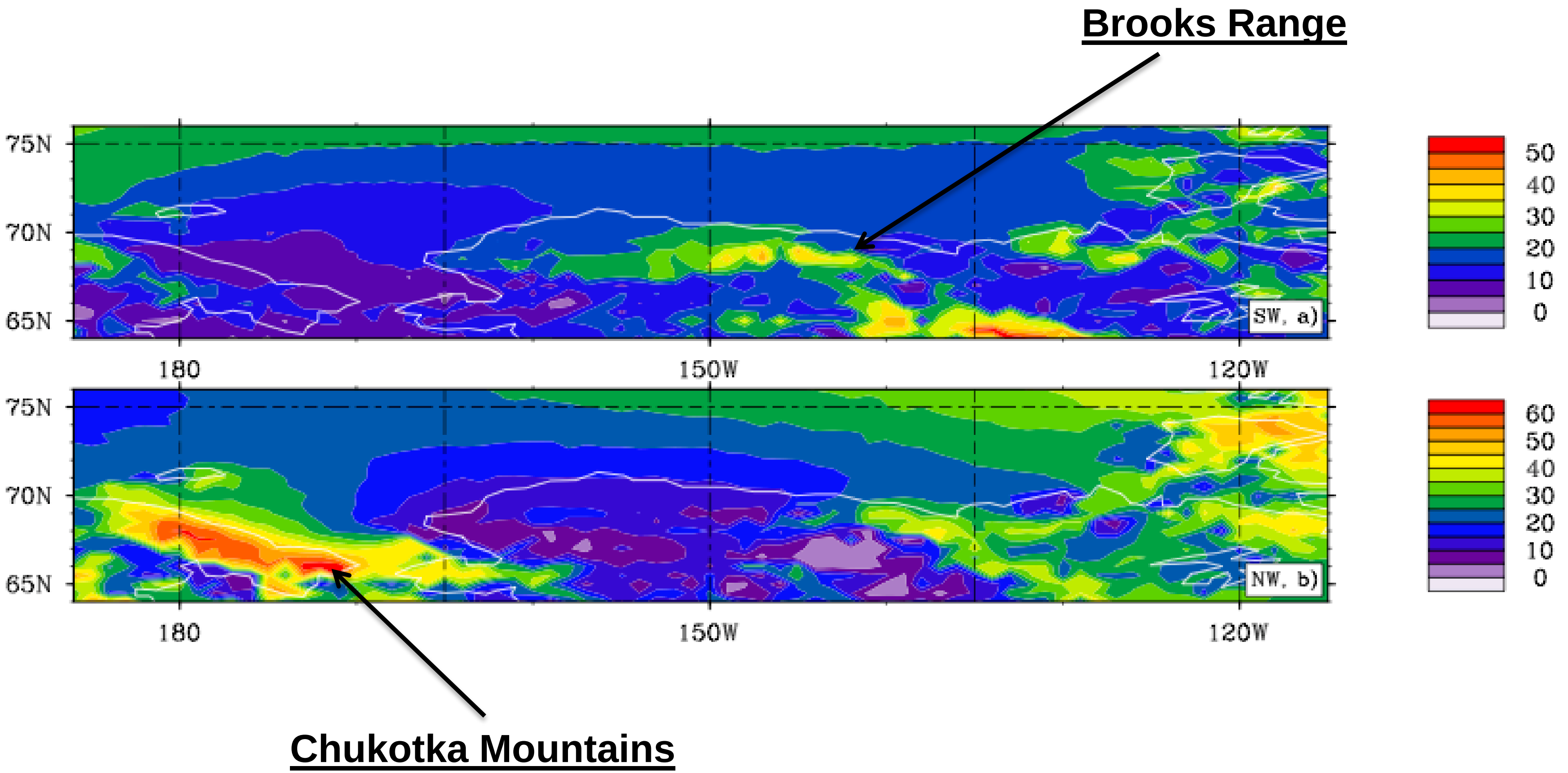


Mountain Barrier Effect



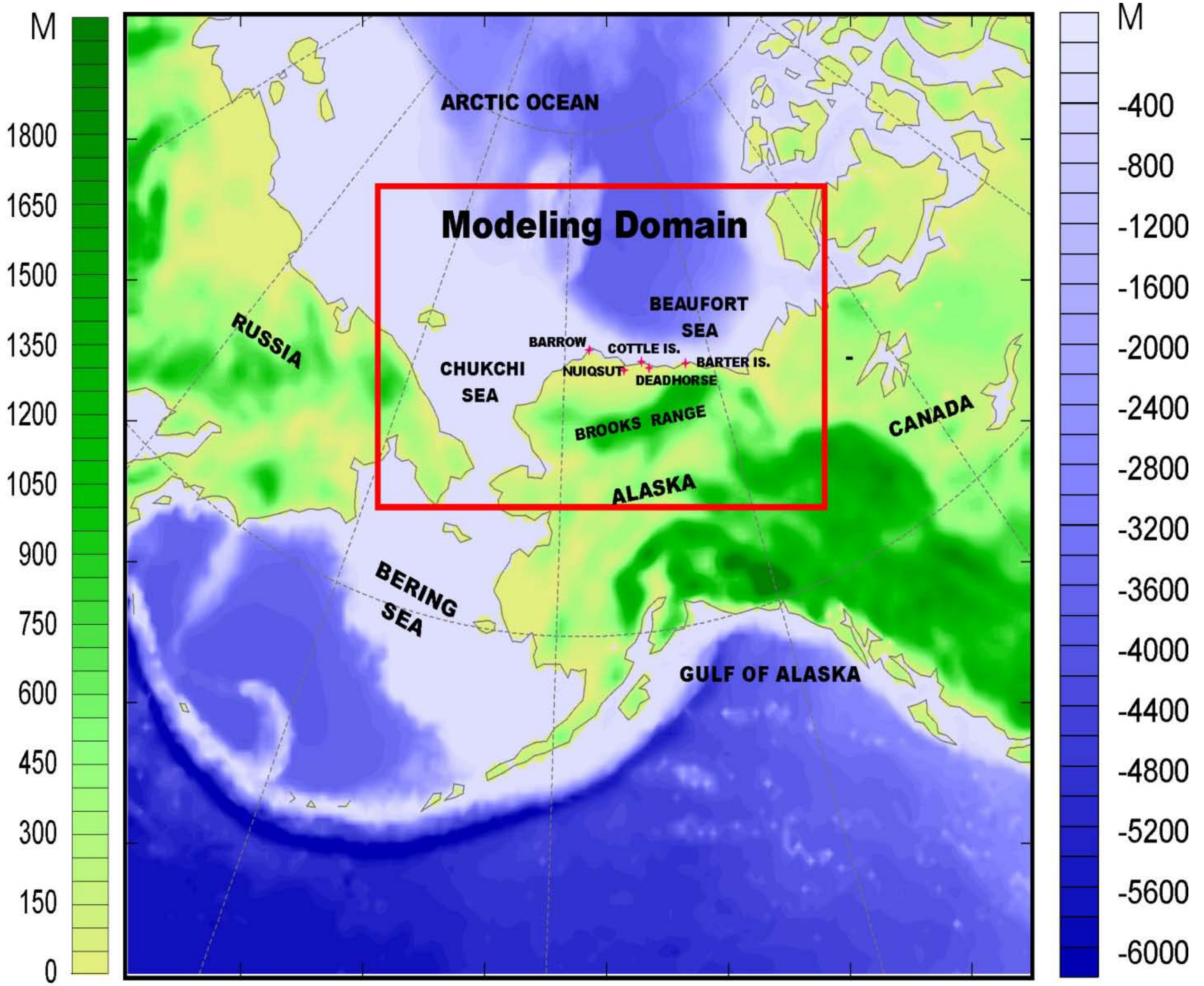
▪ Mesoscale features: Mountain barrier effect.

Frequency of SW (top) and NW (bottom) winds during the cold months (Jan.-May, Oct.-Dec. of 1979-2009)



▪ Model simulation and assimilation – WRF Model.

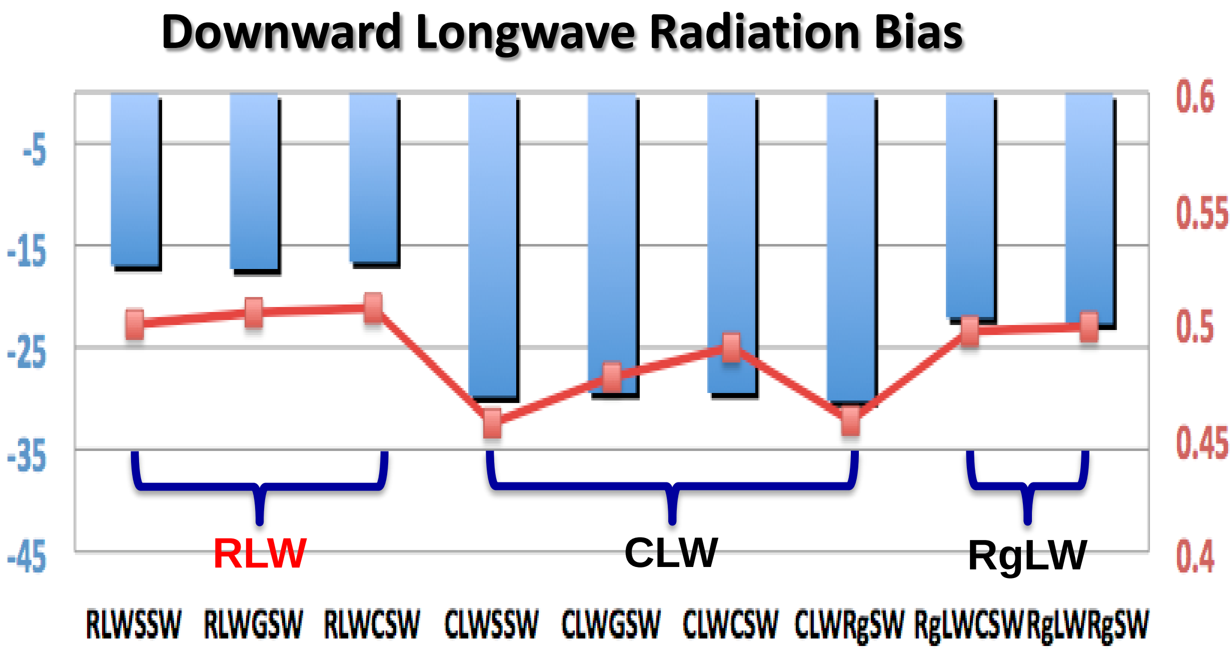
Model Domain

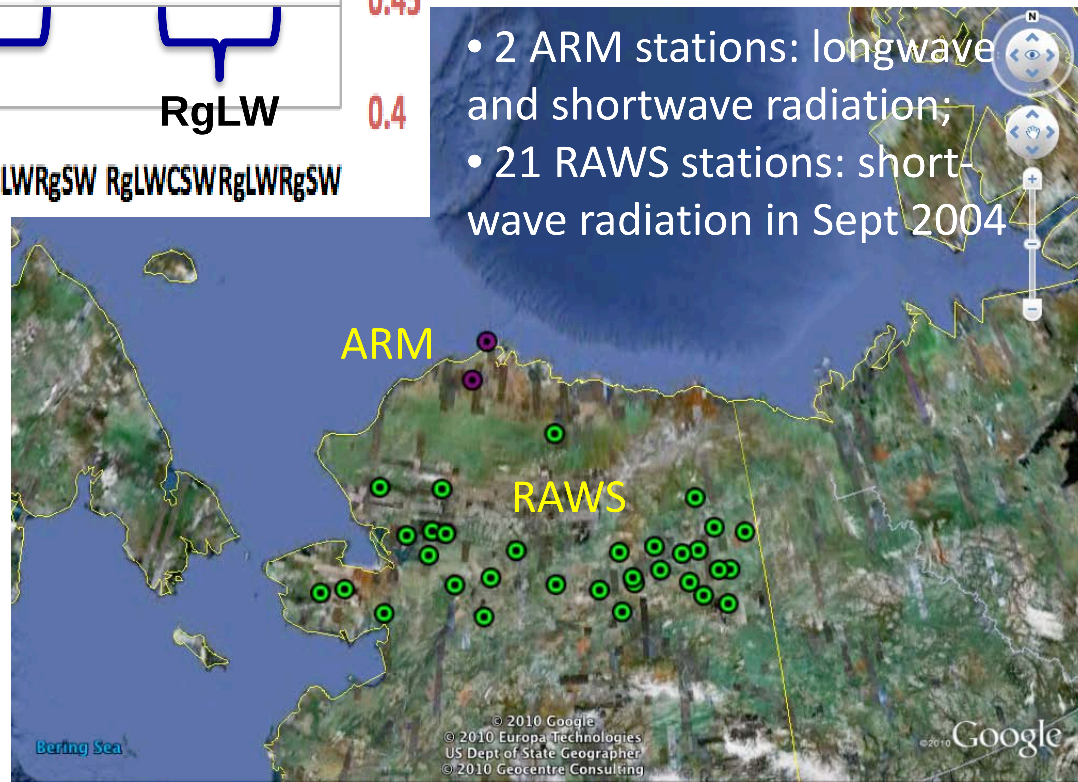


10km resolution

48 vertical levels to 50hpa

▪ Evaluation of model physics against observational data: Example – radiation at ARM stations.

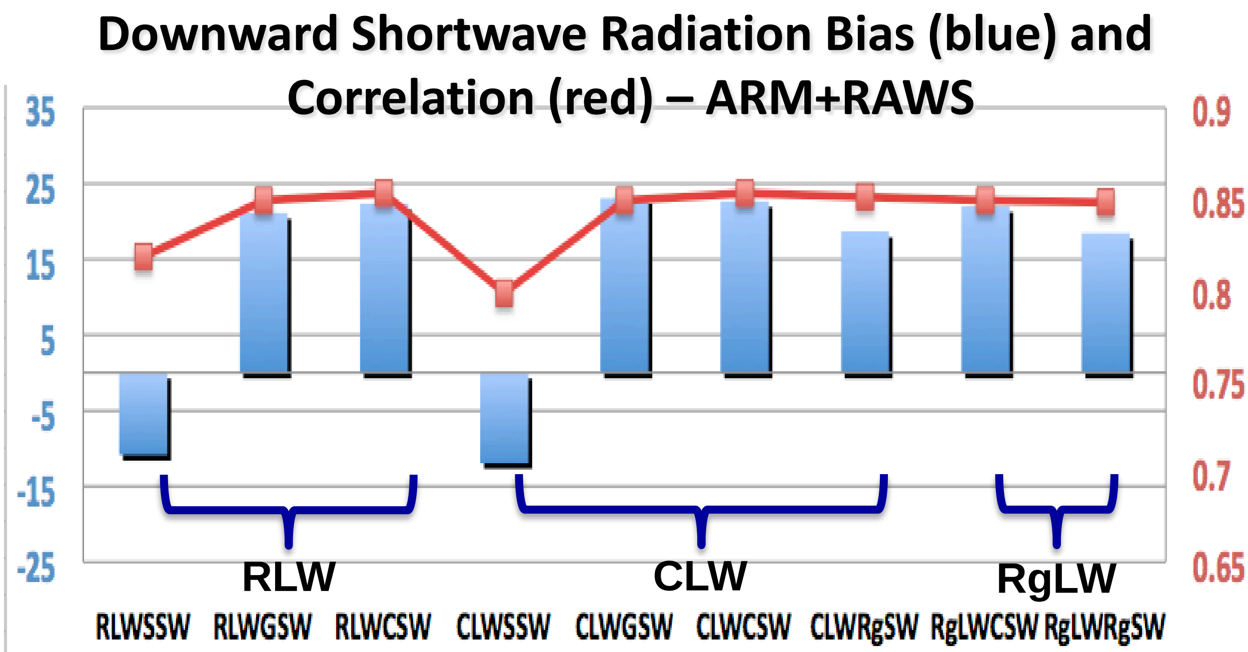


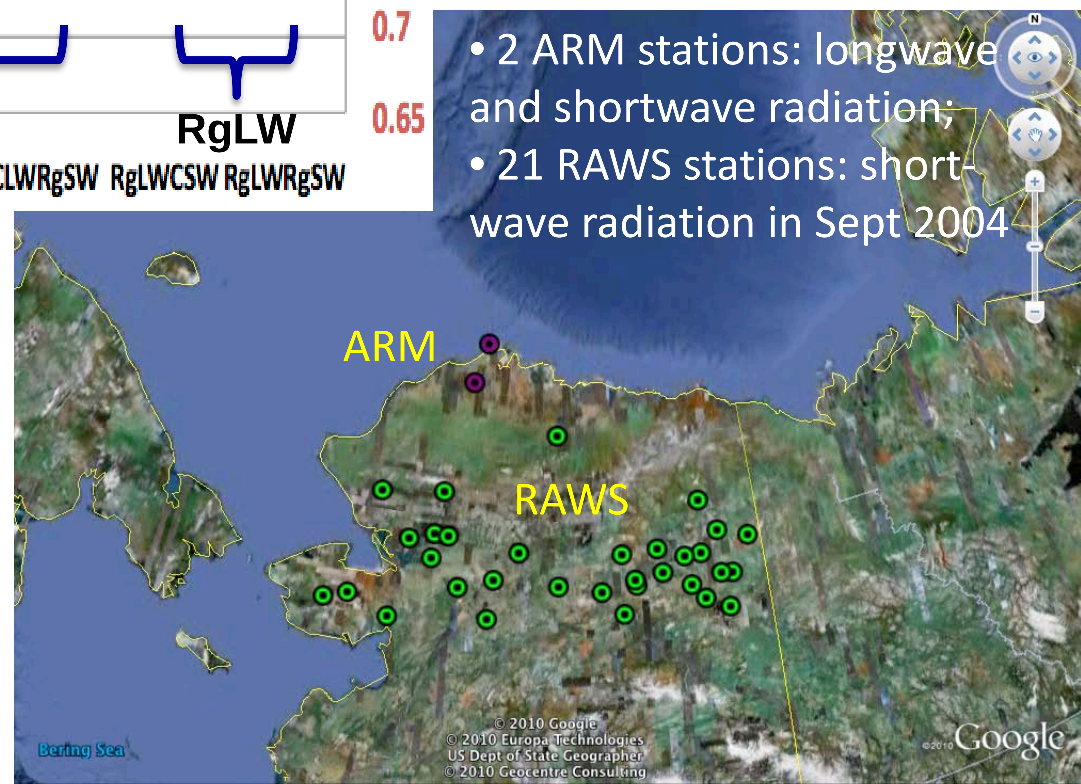


•<u>All longwave schemes have negative bias;</u>

•<u>Shortwave radiation schemes do not show large impacts.</u>

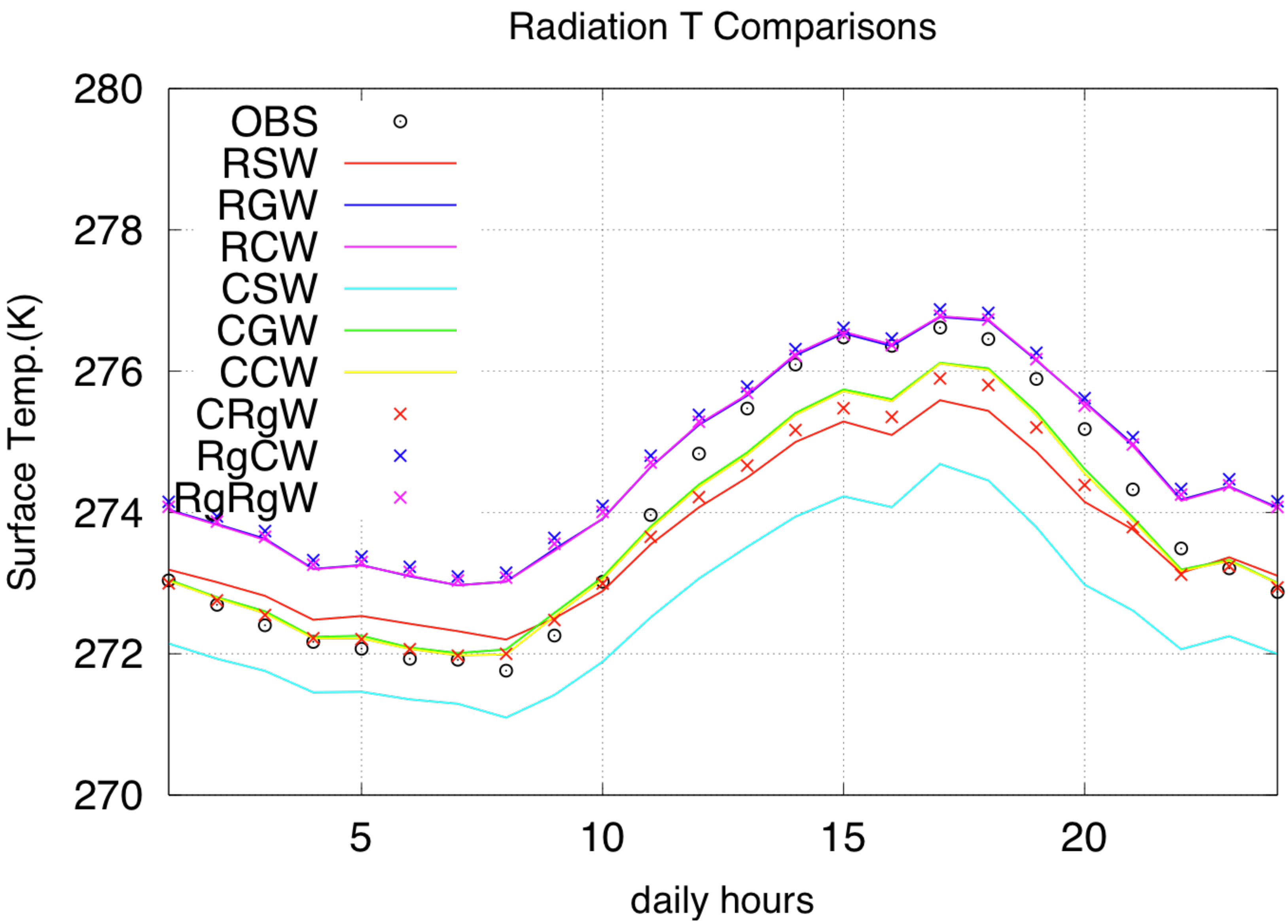
- **Evaluation of model physics against observational data: Example – radiation at ARM+RAWS stations.**



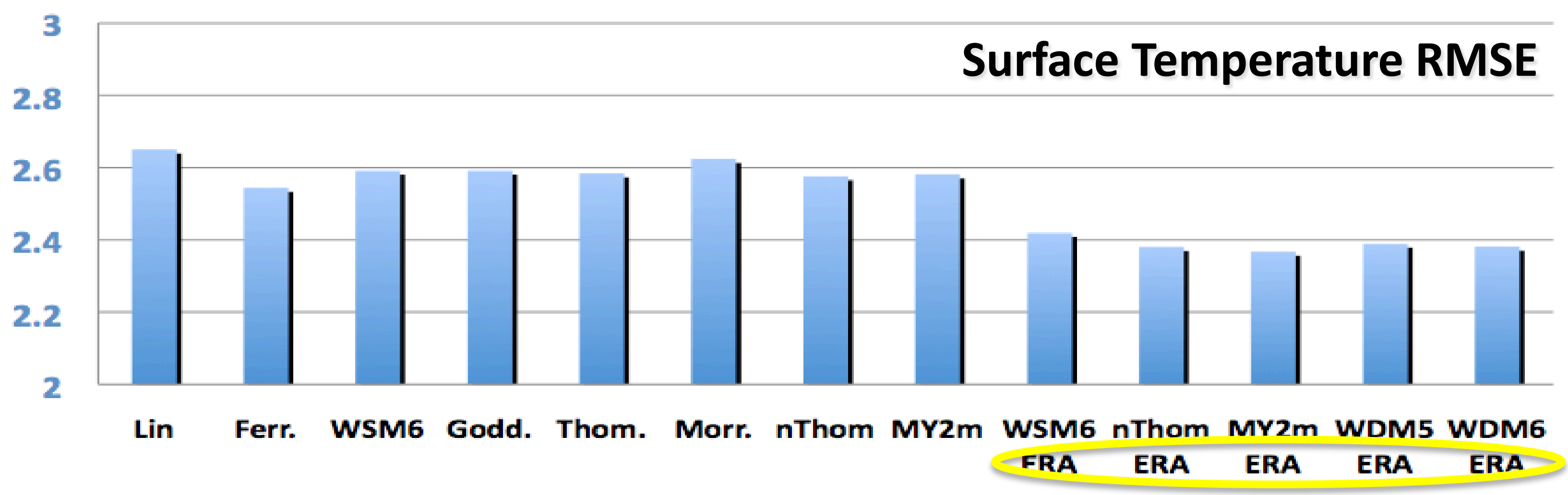


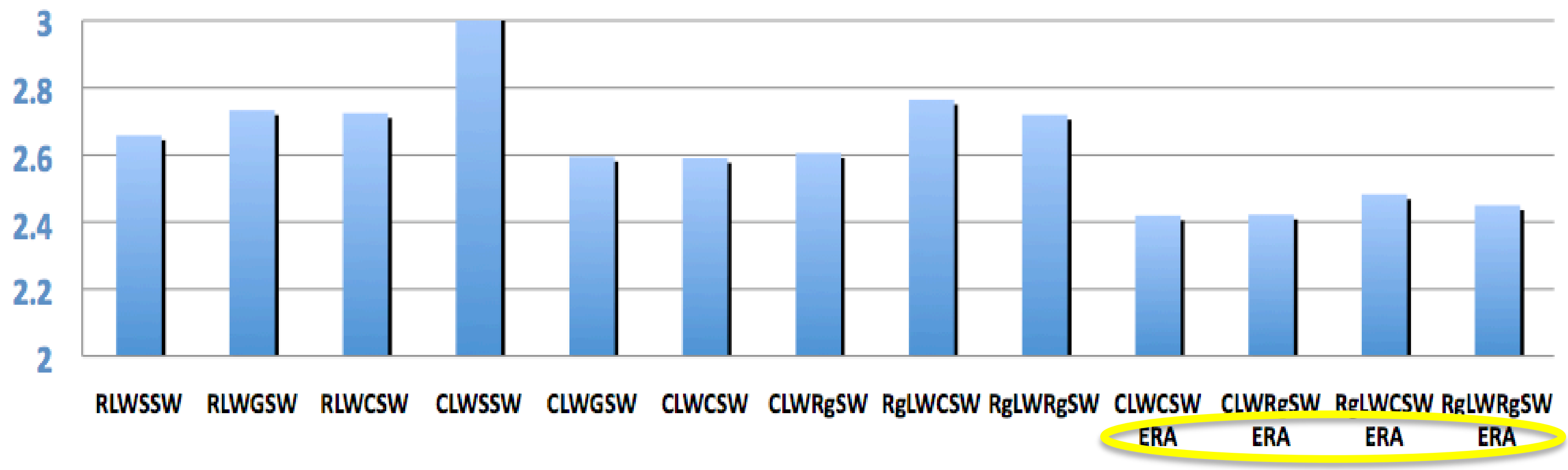
•**<u>All shortwave schemes, except SSW, have positive bias.</u>**

- **Evaluation of model physics against observational data: Example – radiation ~ temperature at all stations.**

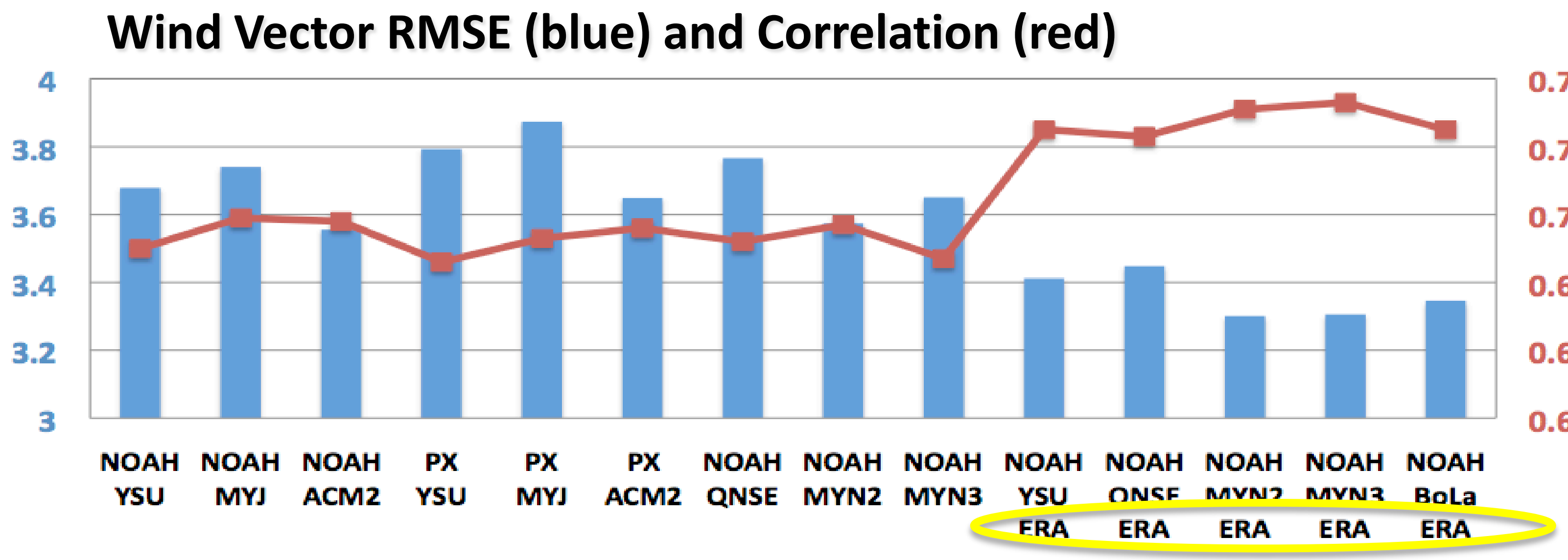


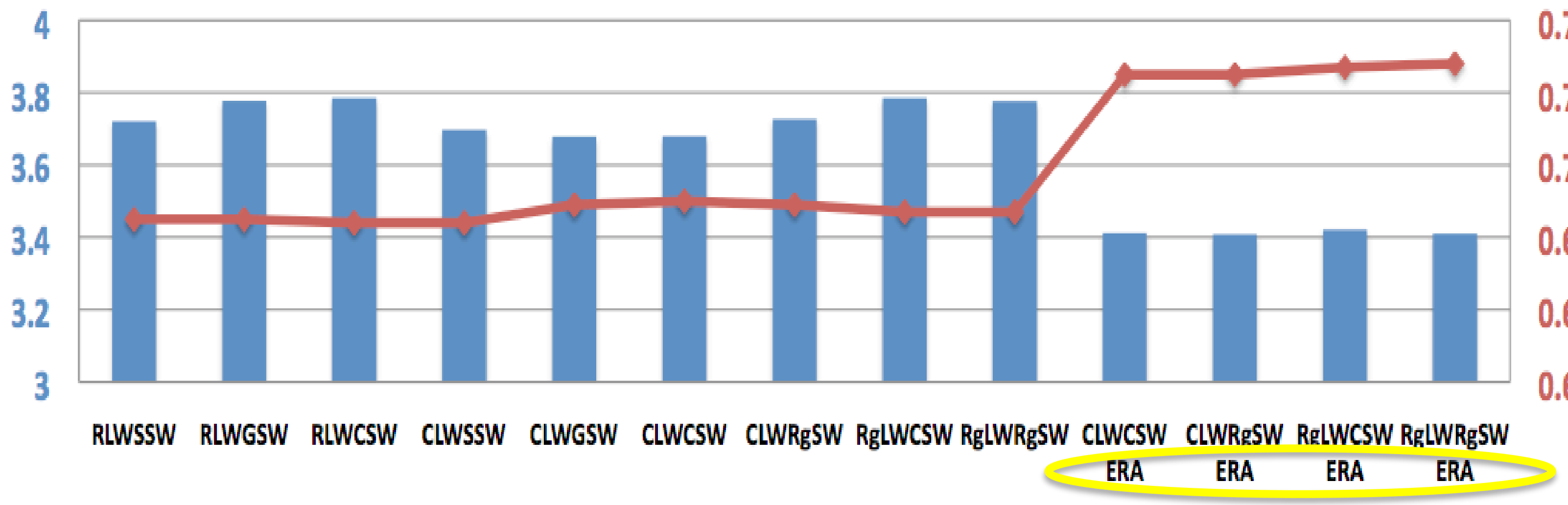
- **Evaluation of large scale forcing against observational data: ERA-I helps reduce surface air temperature bias.**



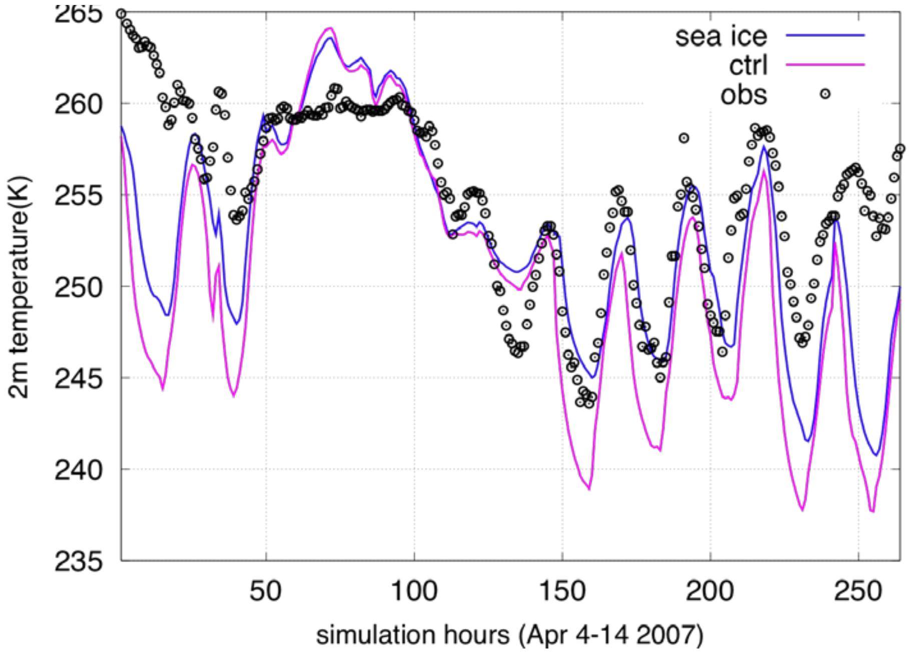


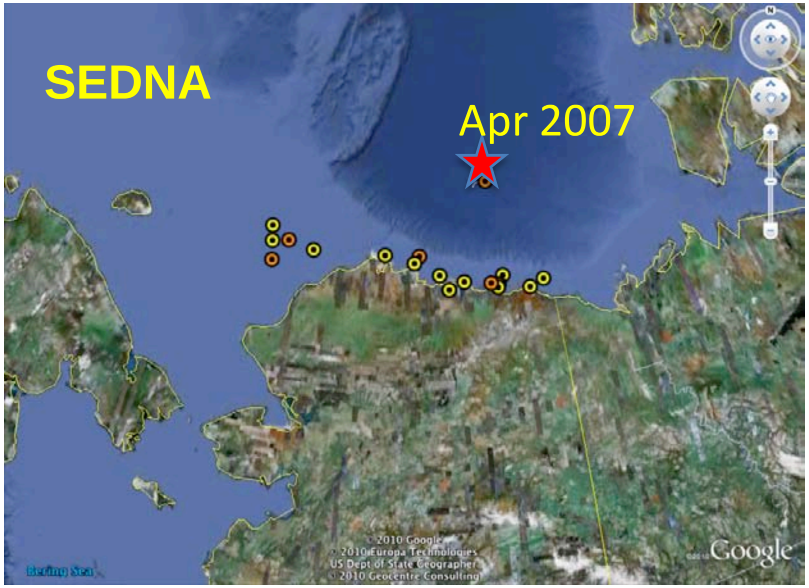
- **Evaluation of large scale forcing against observational data: ERA-I helps reduce surface wind bias.**

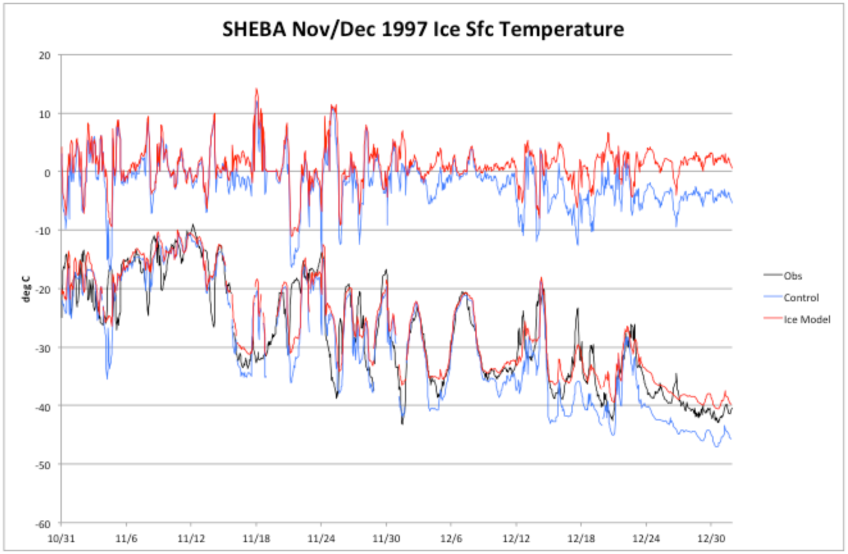


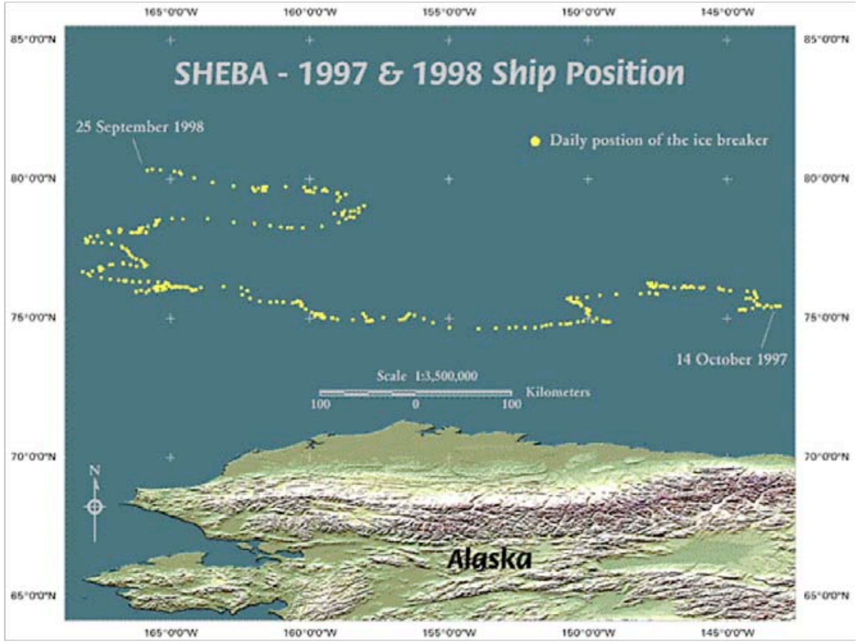


- **Coupling of sea ice thermodynamics with WRF: Help to reduce cold surface temperature bias.**



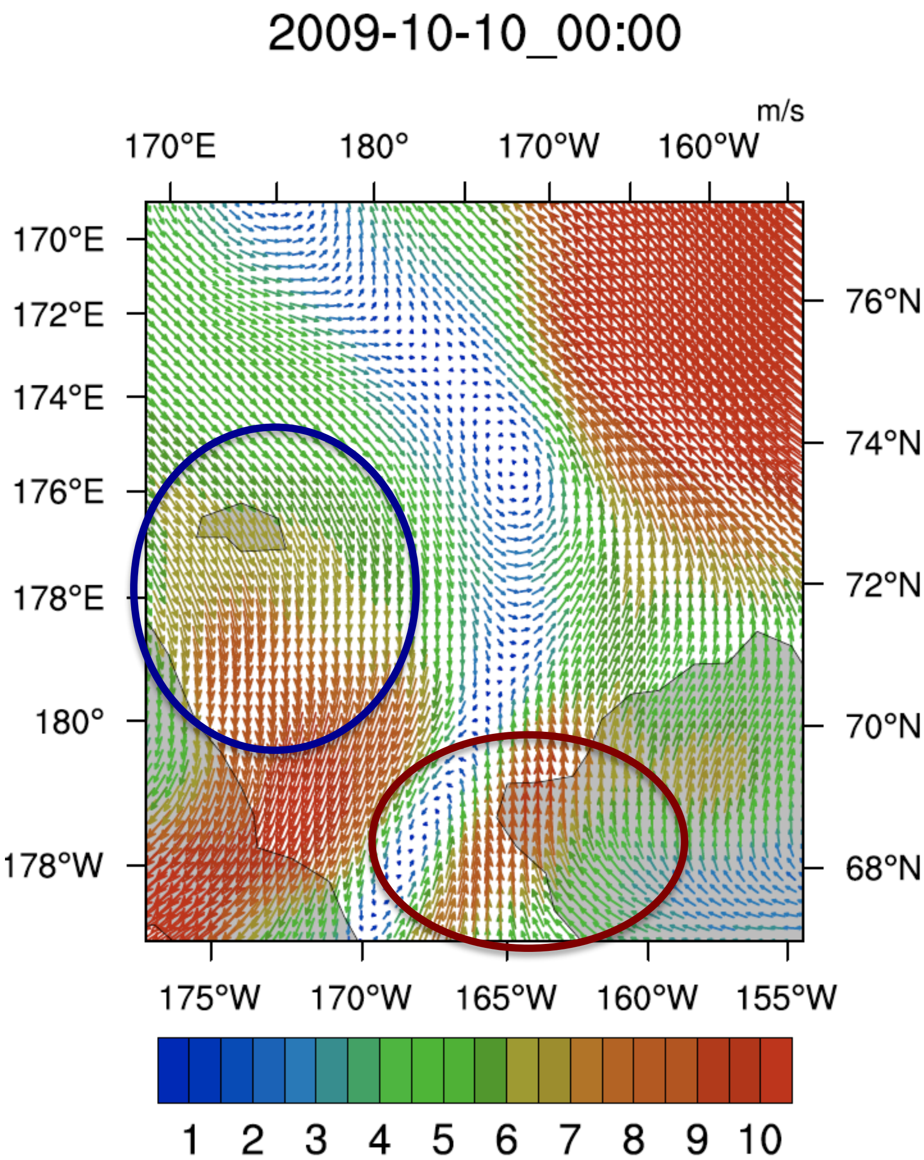




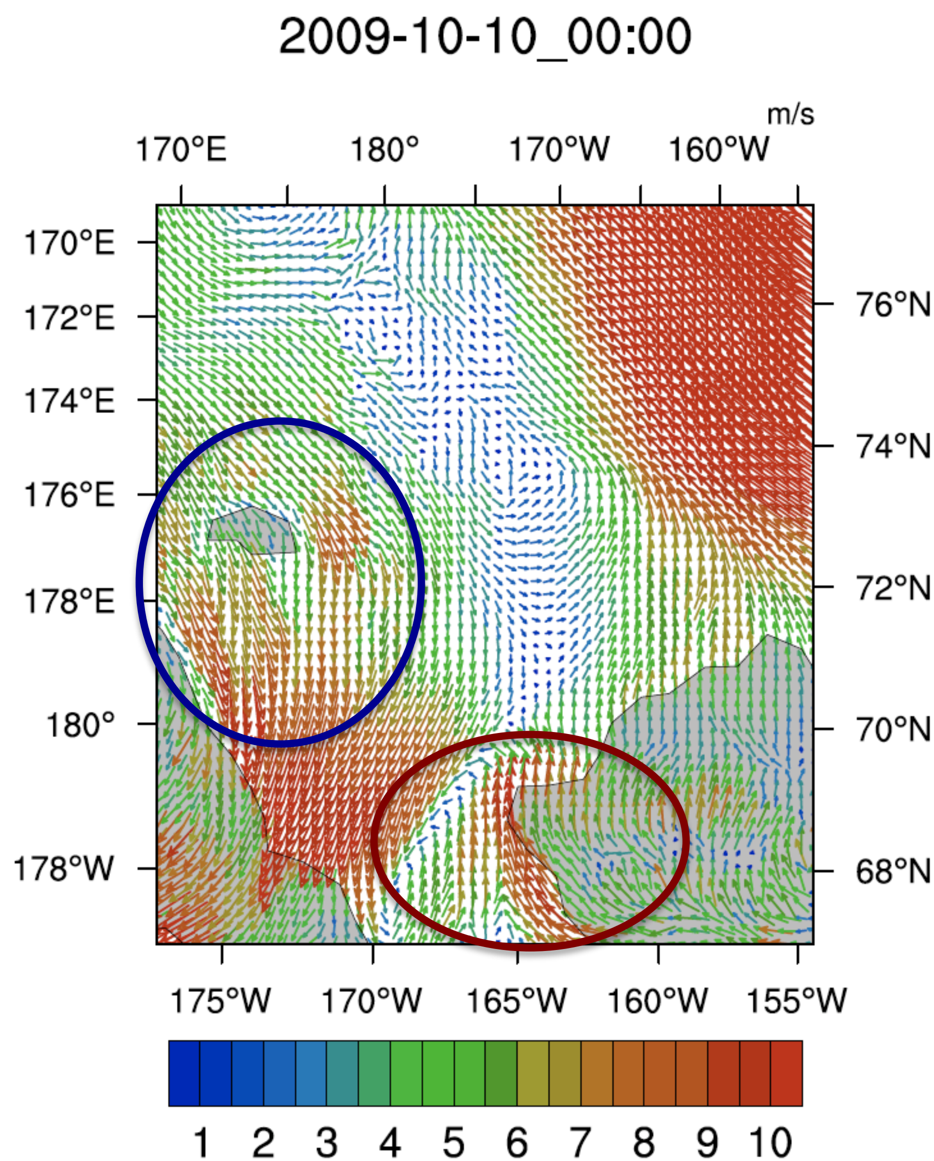


- **Experimental simulation for 2009: Model-Data comparison – snapshot at 00 UTC Oct 10, 2009**

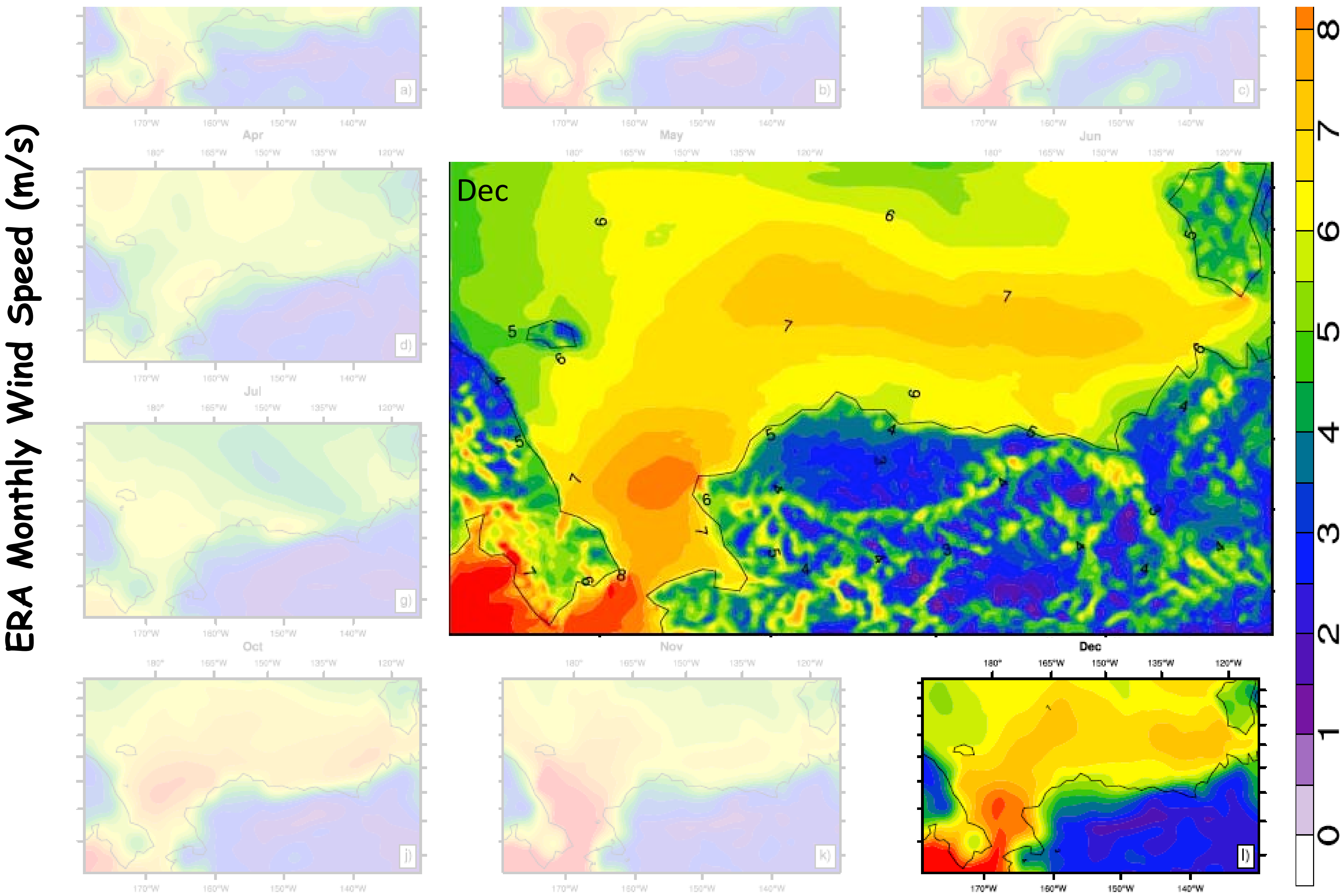
ERA-I



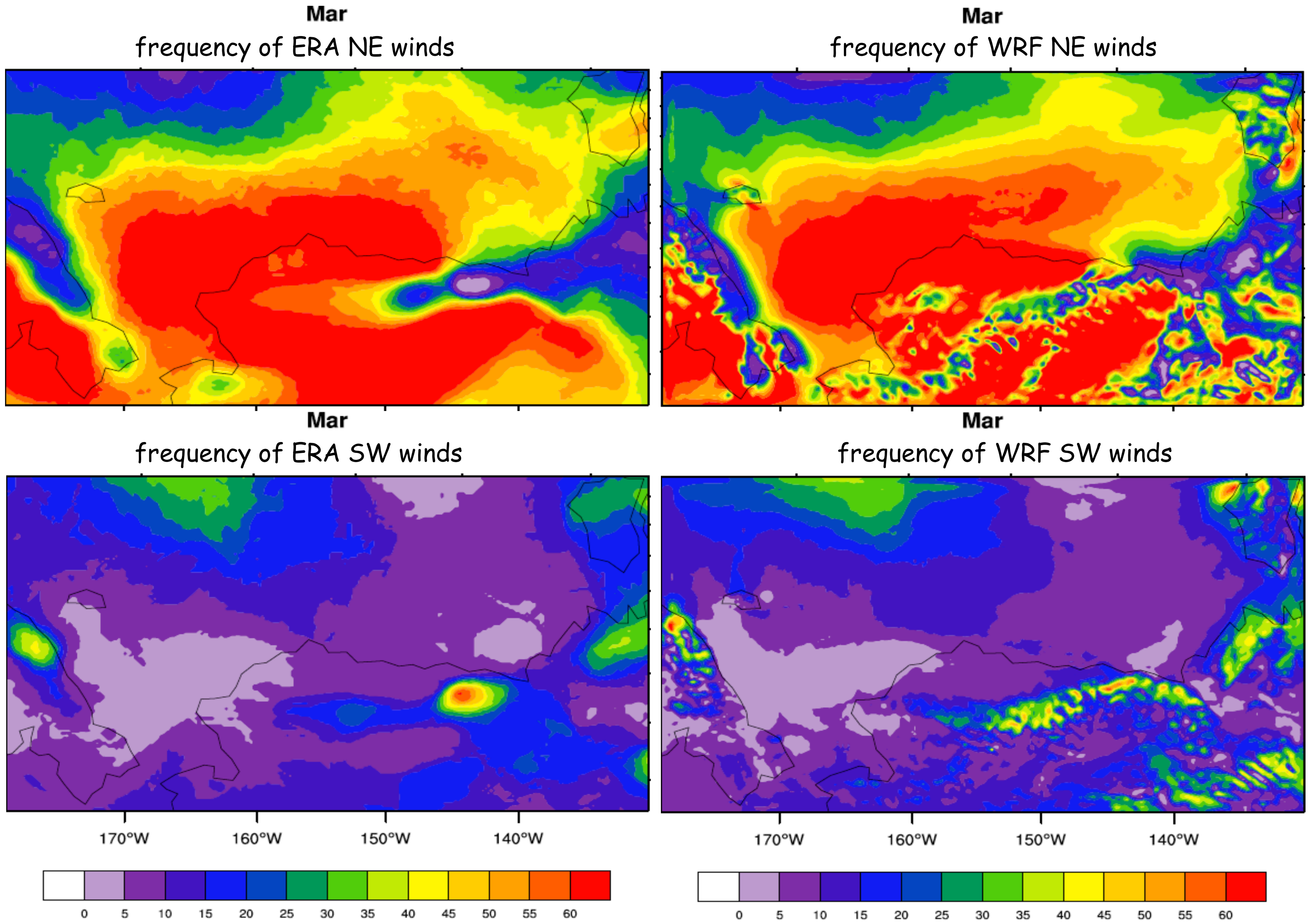
Model



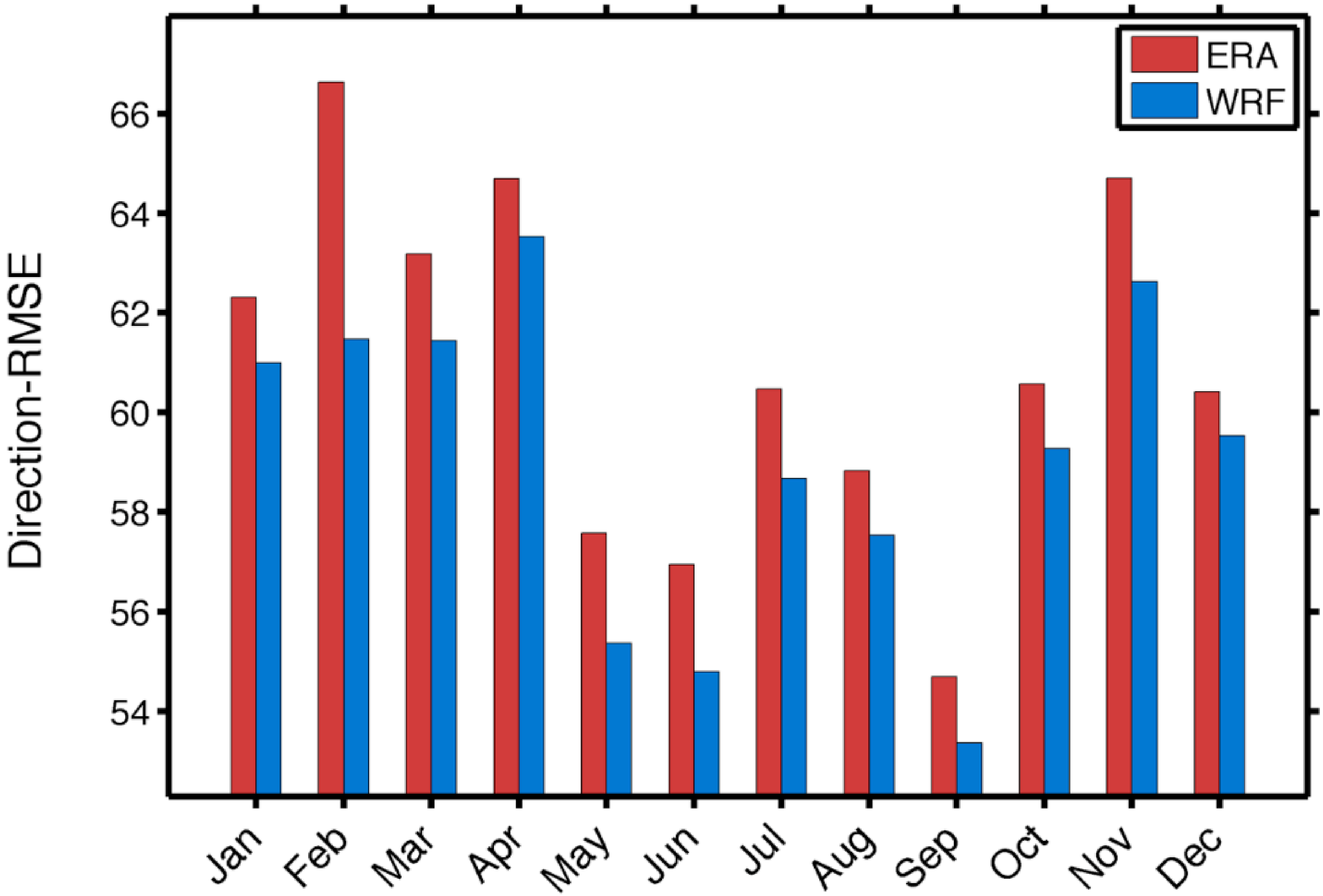
Experimental simulation for 2009: Model-Data comparison – monthly wind speed



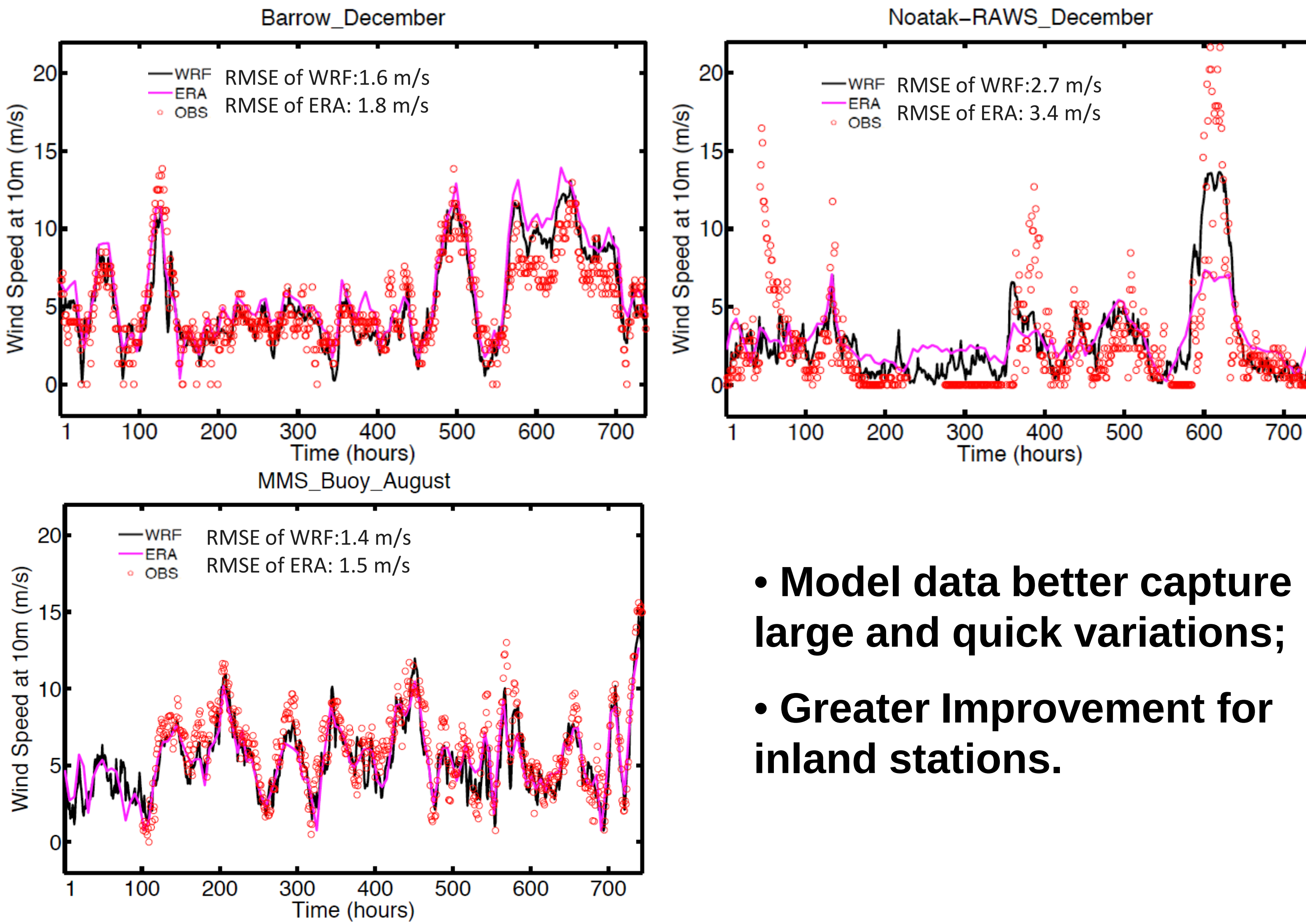
- **Experimental simulation for 2009: Model-Data comparison – frequencies of NE winds and SW winds**



- **Experimental simulation for 2009: Model-Data comparison – RMSE of monthly wind directions**

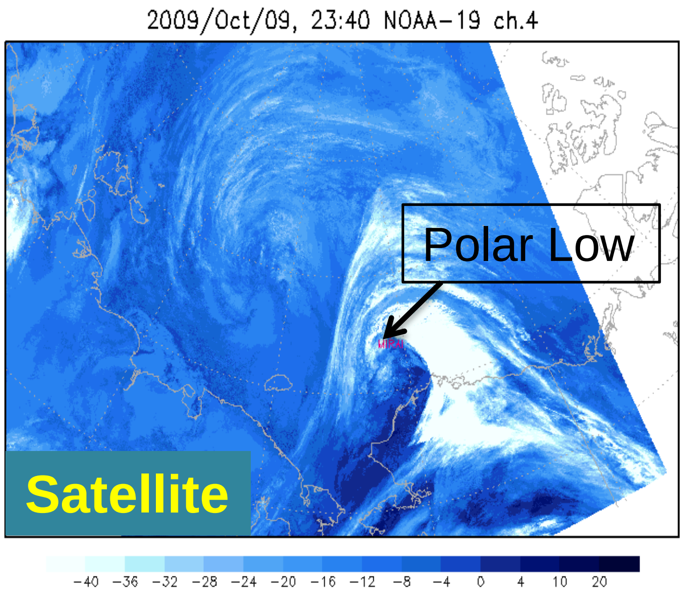


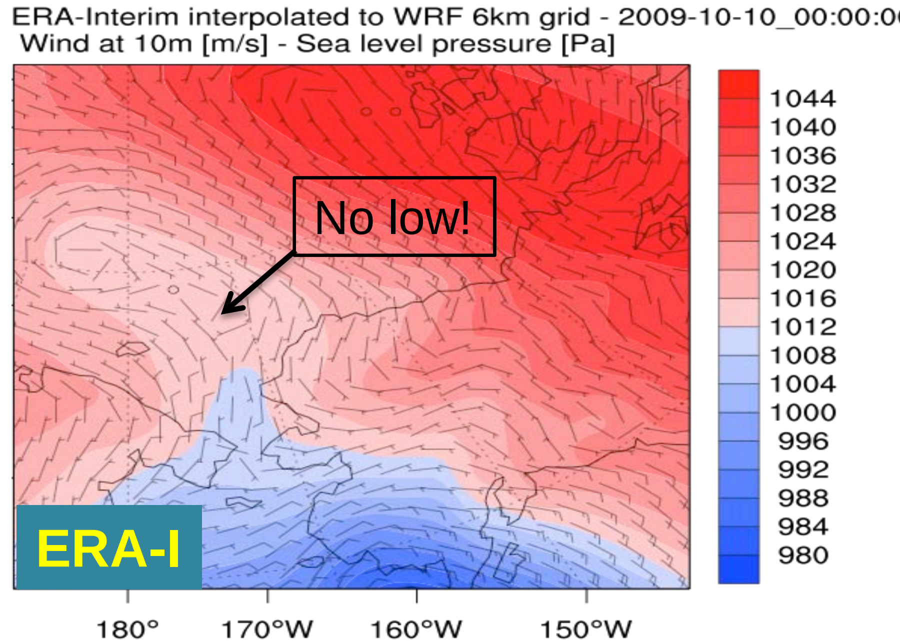
▪ Experimental simulation for 2009: Model-Data comparison – time series against station data

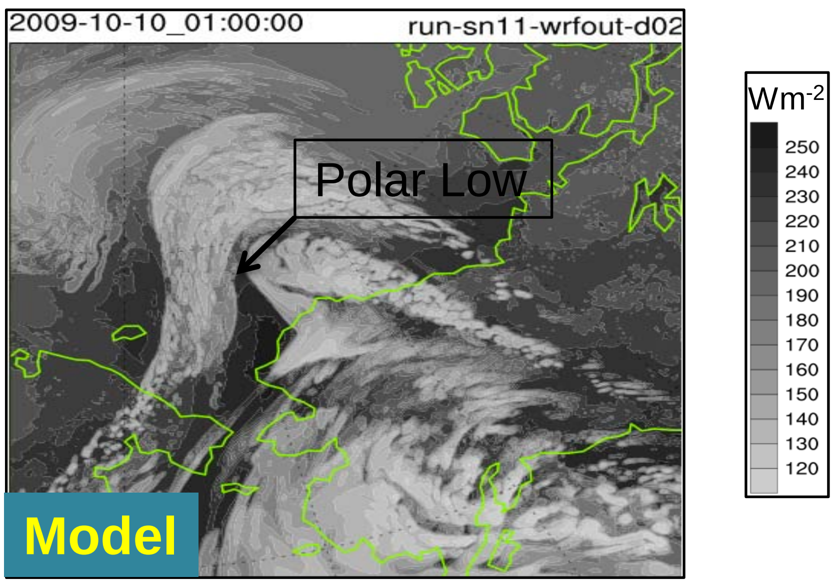


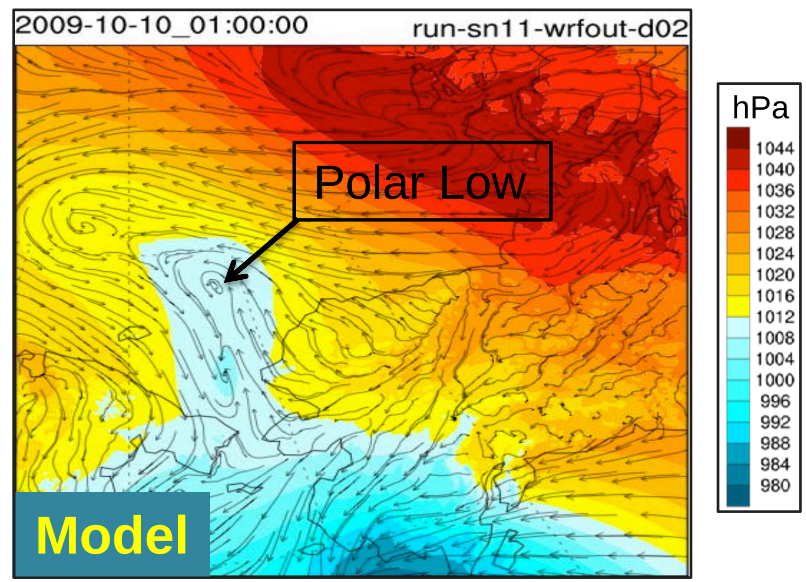
- **Model data better capture large and quick variations;**
- **Greater Improvement for inland stations.**

▪ Simulation of mesoscale extreme event – The model better captures the polar low than the ERA data









Summary

1. Large scale atmospheric circulation has experienced large temporal fluctuations and radical spatial shifts, impacting surface wind and playing a central role in the recently observed rapid Arctic changes;

2. Surface wind in the Beaufort and Chukchi seas has its own specific regional features, characterized by the increased tendency of east wind, wind speed, and frequency of extreme winds;

3. Mesoscale model shows improved representation of finer scale meteorological systems and processes, helping better understanding regional wind variability and change and better simulating ocean/sea ice/oil spill dispersions.

   - Carefully selected physics is essential for successful model simulation
   - sea ice coupling improves surface temperature simulation
   - high quality large scale forcing (IC/BC) helps reduce model biases

Ocean Circulation

Tom Weingartner

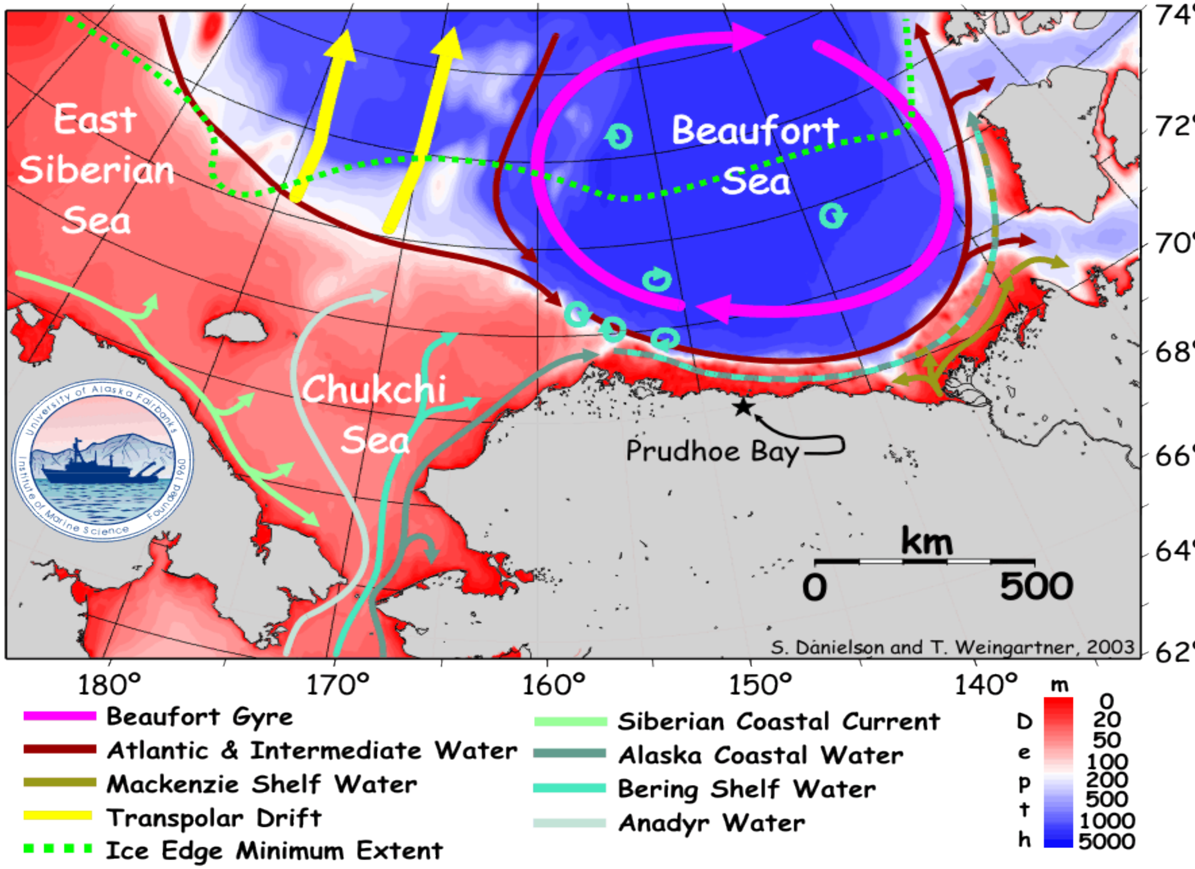
Institute of Marine Science, University of Alaska

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

SAIC: Maclean, VA March 29-31, 2011

Outline

1. Regional Setting
2. Bering Strait (the “southern” boundary)
3. Northeast Chukchi Sea
4. Beaufort Sea
5. Summary



The Chukchi/Beaufort Setting

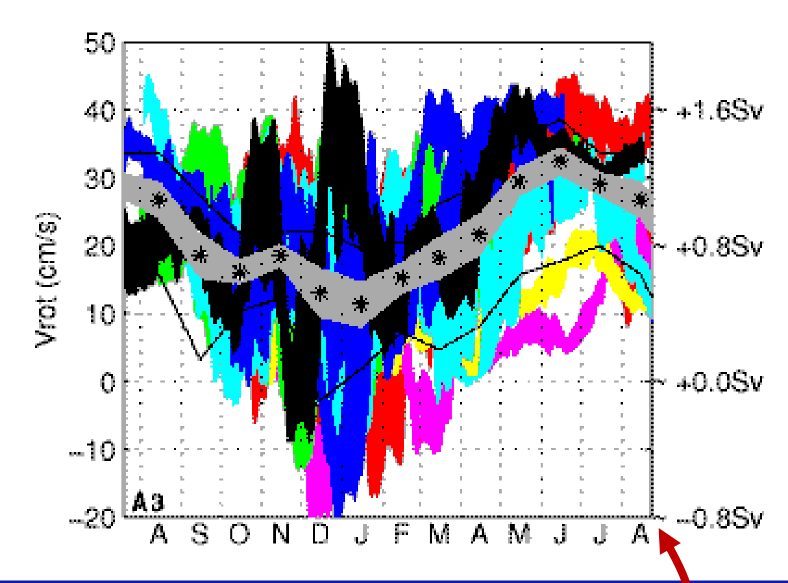
Global Processes drive the Pacific and Atlantic inflows and the Beaufort Gyre.

Both shelves communicate with one another.

Linkages with:

- Basin via shelfbreak: up/downwelling and "eddy" exchanges
- East Siberian Sea
- Mackenzie Beaufort Shelf

Bering Strait Seasonal Cycles



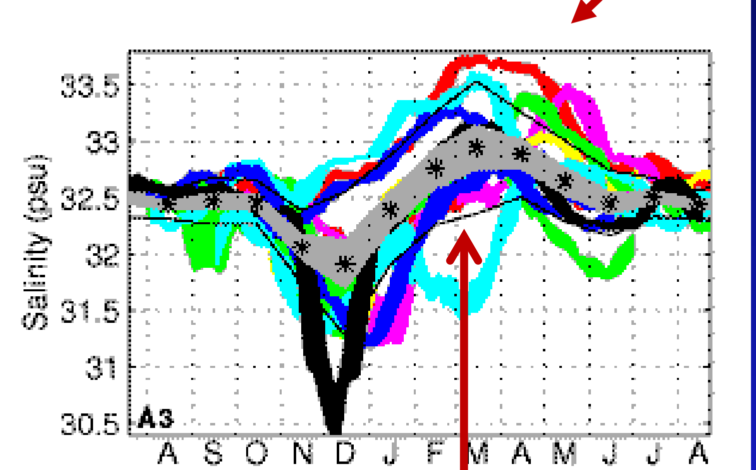
Monthly Transports

Minimum Winter: 0.5 Sv
Maximum Summer: 1.2 Sv
Mean: 0.8 Sv
Variability: largely wind driven

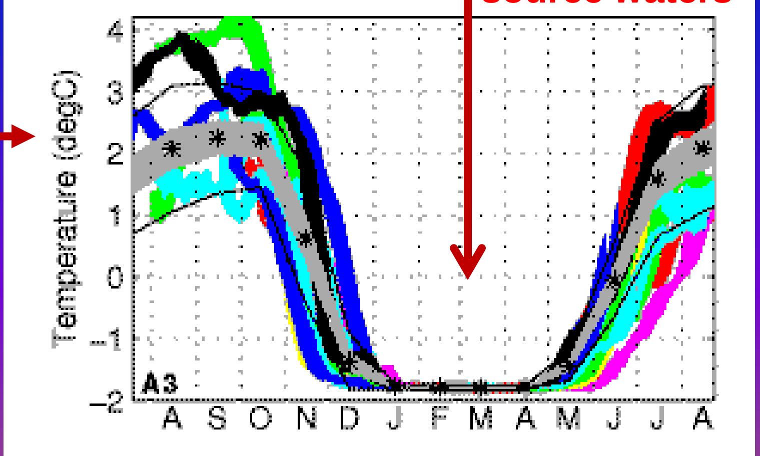
Salinity

Minimum fall
- runoff & mixing

Maximum winter
- ice formation



Upper halocline source waters



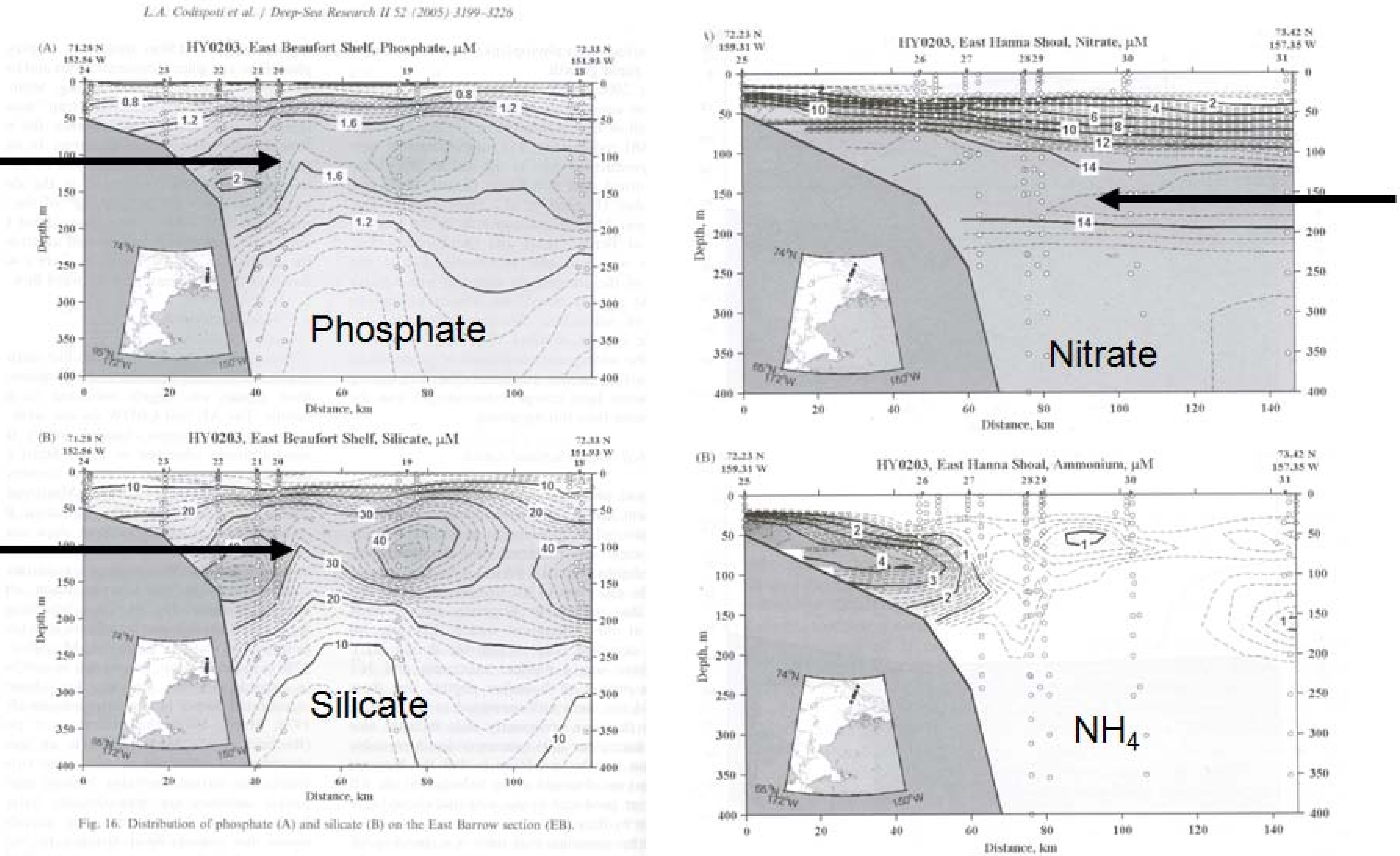
Temperature

Minimum winter
- freezing
- duration: 4-6 mos.

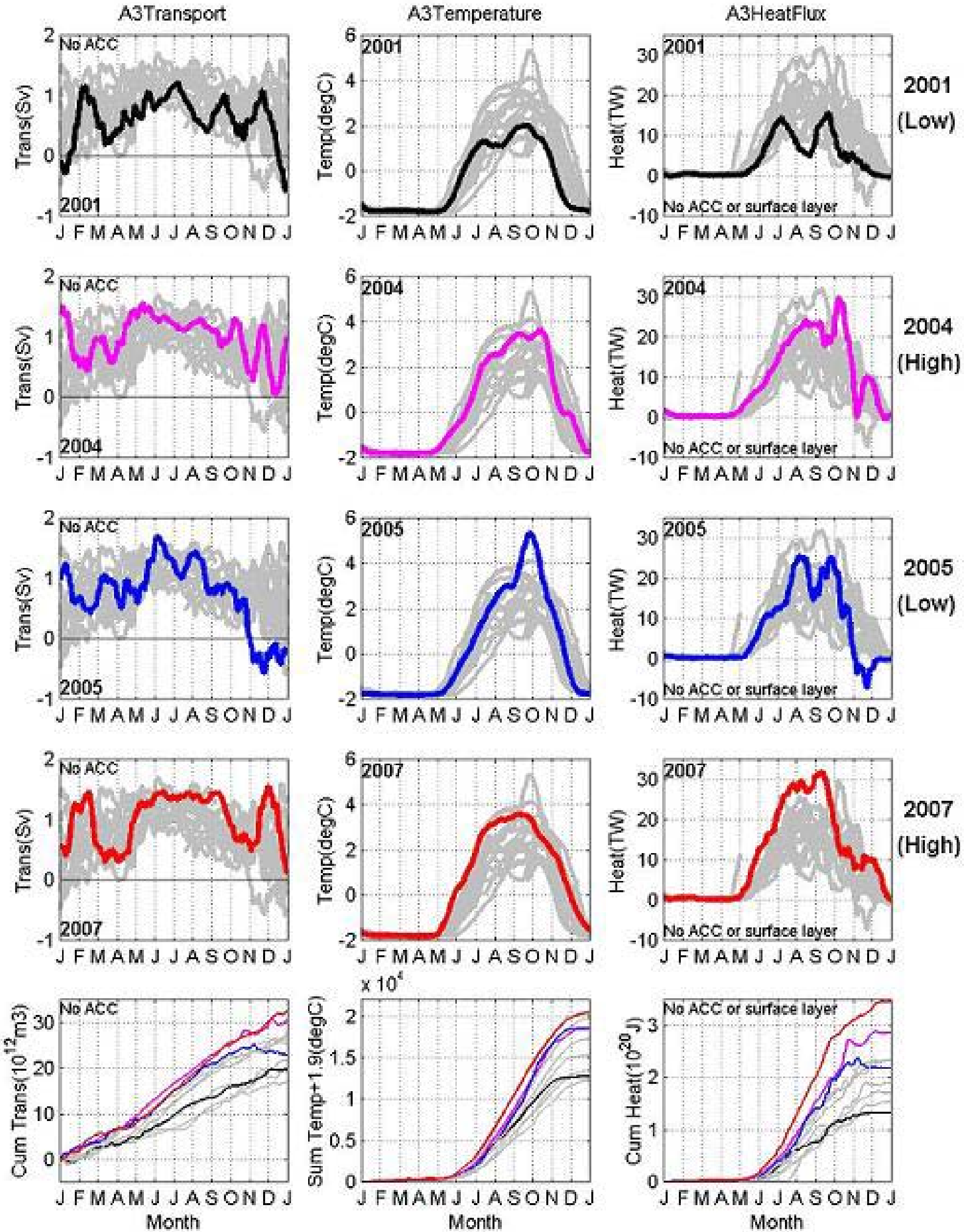
Maximum summer

(Woodgate, Aagaard, and Weingartner, 2005)

Nutrient-rich Pacific Waters enter the Upper Halocline



"... the flux of DIN through Bering Strait is the major chemical influence on biological production in the region." (Codispoti et al., 2005)



Bering Strait Summer heat flux variability

Transport: 0.7 to 1.4 Sv
Temperature: 2 to 5^0C

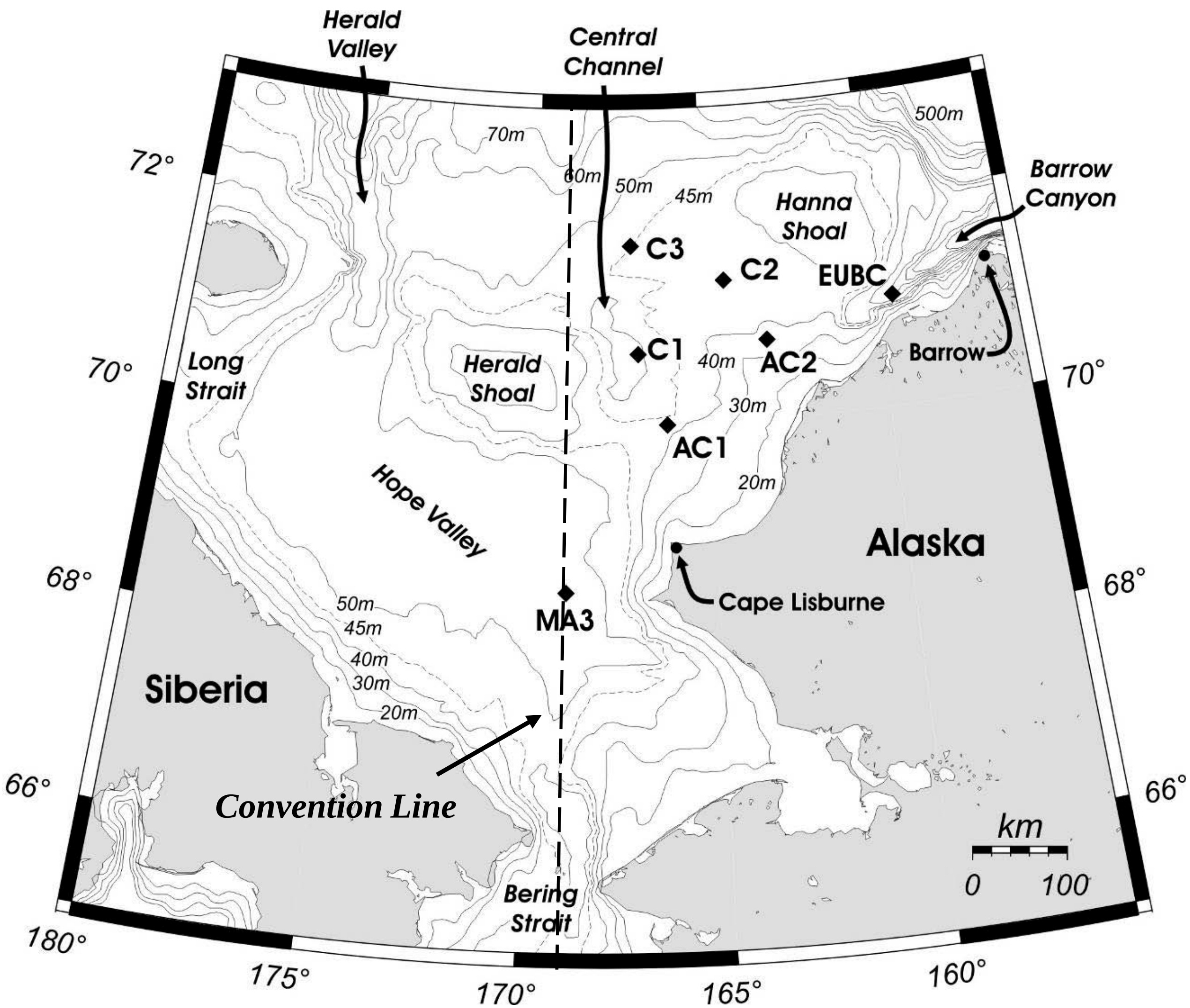
Jun-Oct Cumulative heat flux:
Bering Strait: $1\text{-}3\times10^{20}$ J

~net solar radiation influx

important to regional ice melt

(Woodgate, ,Weingartner, and Lindsay, 2010)

The Chukchi Sea: Bathymetry is Key!!



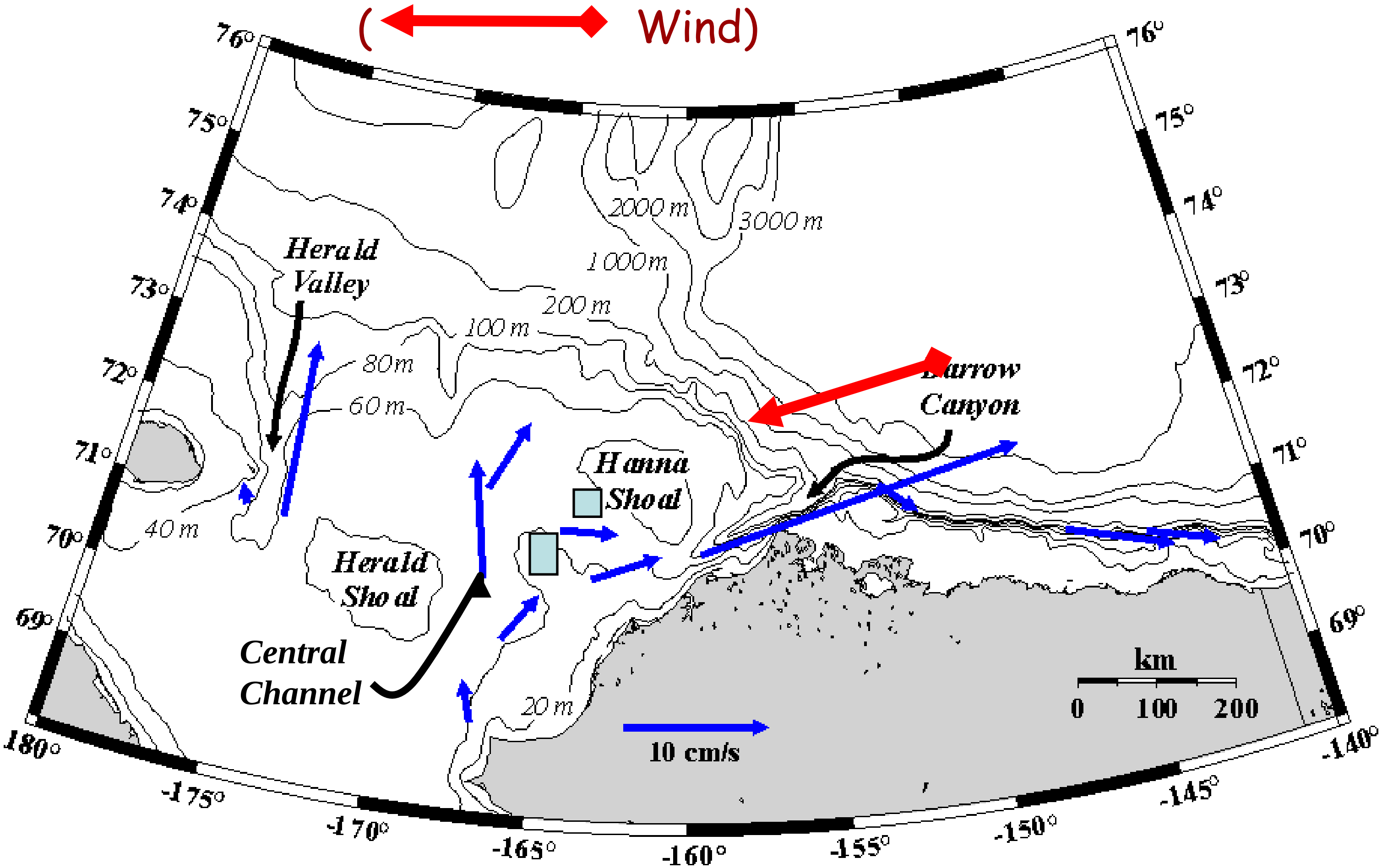
Shoals

Channels

Canyons

"low-relief" regions

Composite Mean Flow Field From Sub-surface Measurements (1990 – 1995)

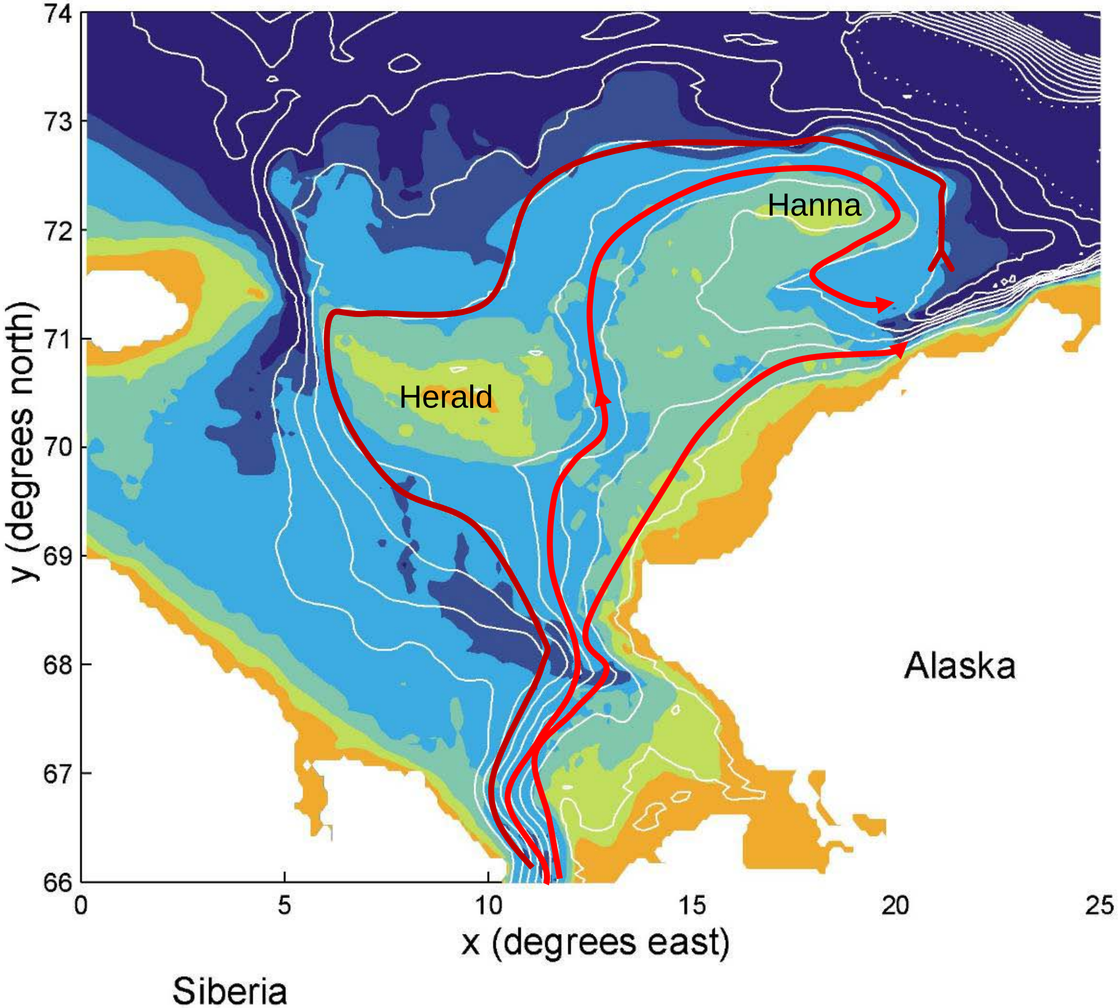


Mean Flow: bathymetrically "steered" & opposes wind

Transit Times (Bering Strait – Barrow Canyon):

Summer: ~3 months; winter 6 – 9 months

Model Mean Streamlines
Vertically integrated transport



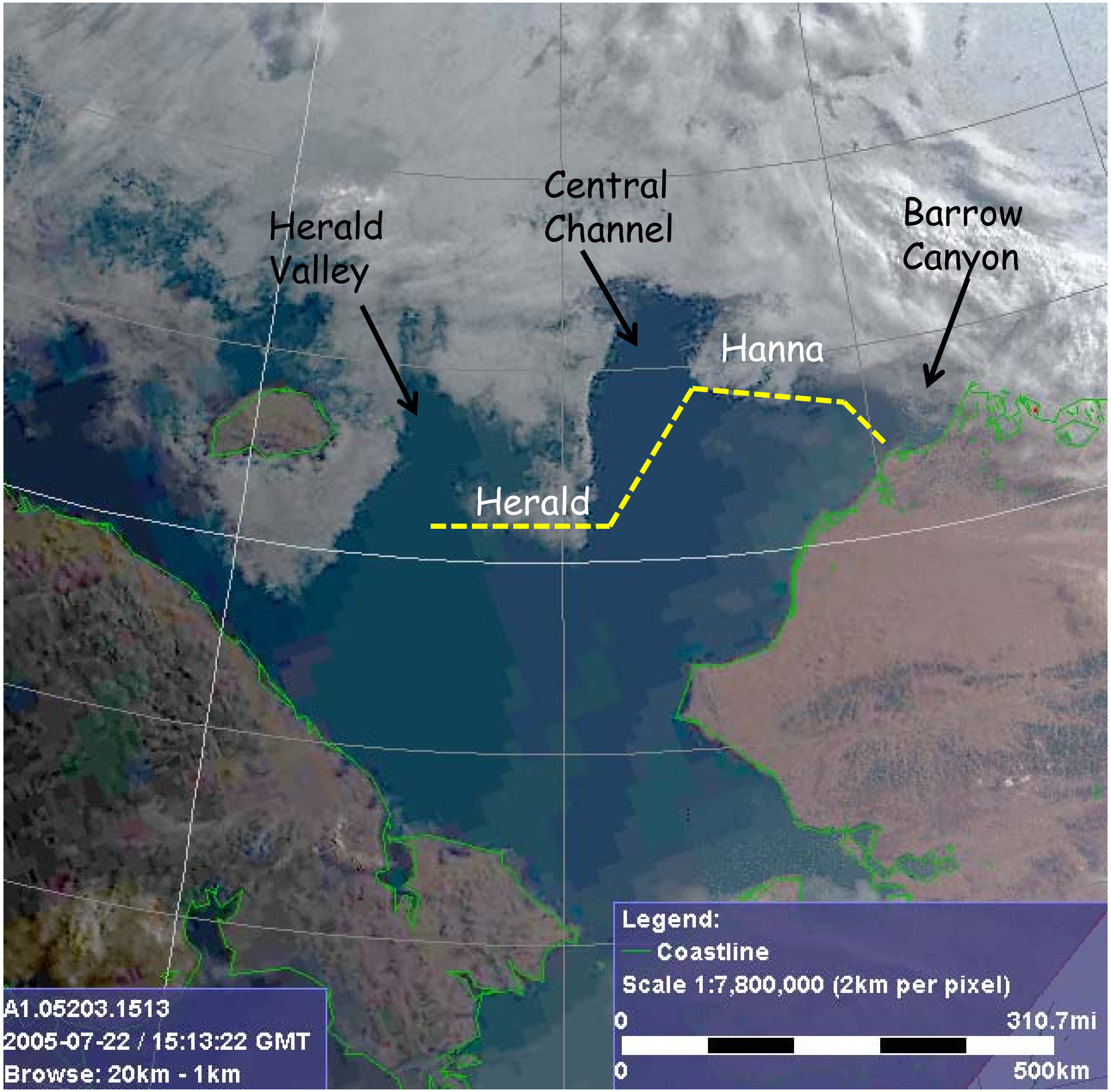
Mean flow is "northward" and bathymetrically "steered".

Shoals are isolated "trapping"

Western & central shelf feeds eastern shelf & Barrow Canyon

Shelfbreak flow intensified north of Hanna Shoal

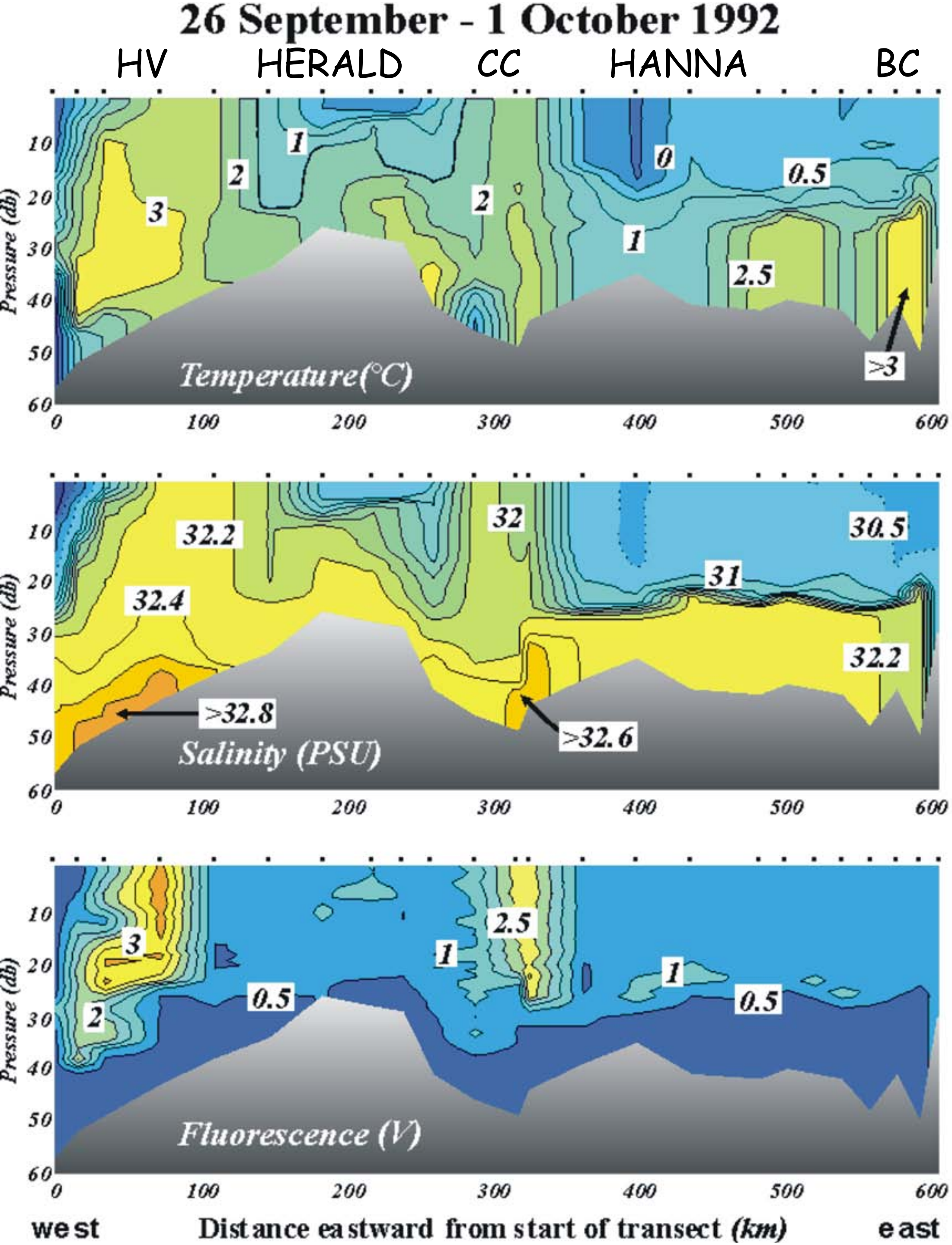
(Courtesy M. Spall, WHOI)



The Mean Flow is reflected in the ice-edge meltback pattern:

Shoals:
Trap Ice

Channels:
Enhanced Melt



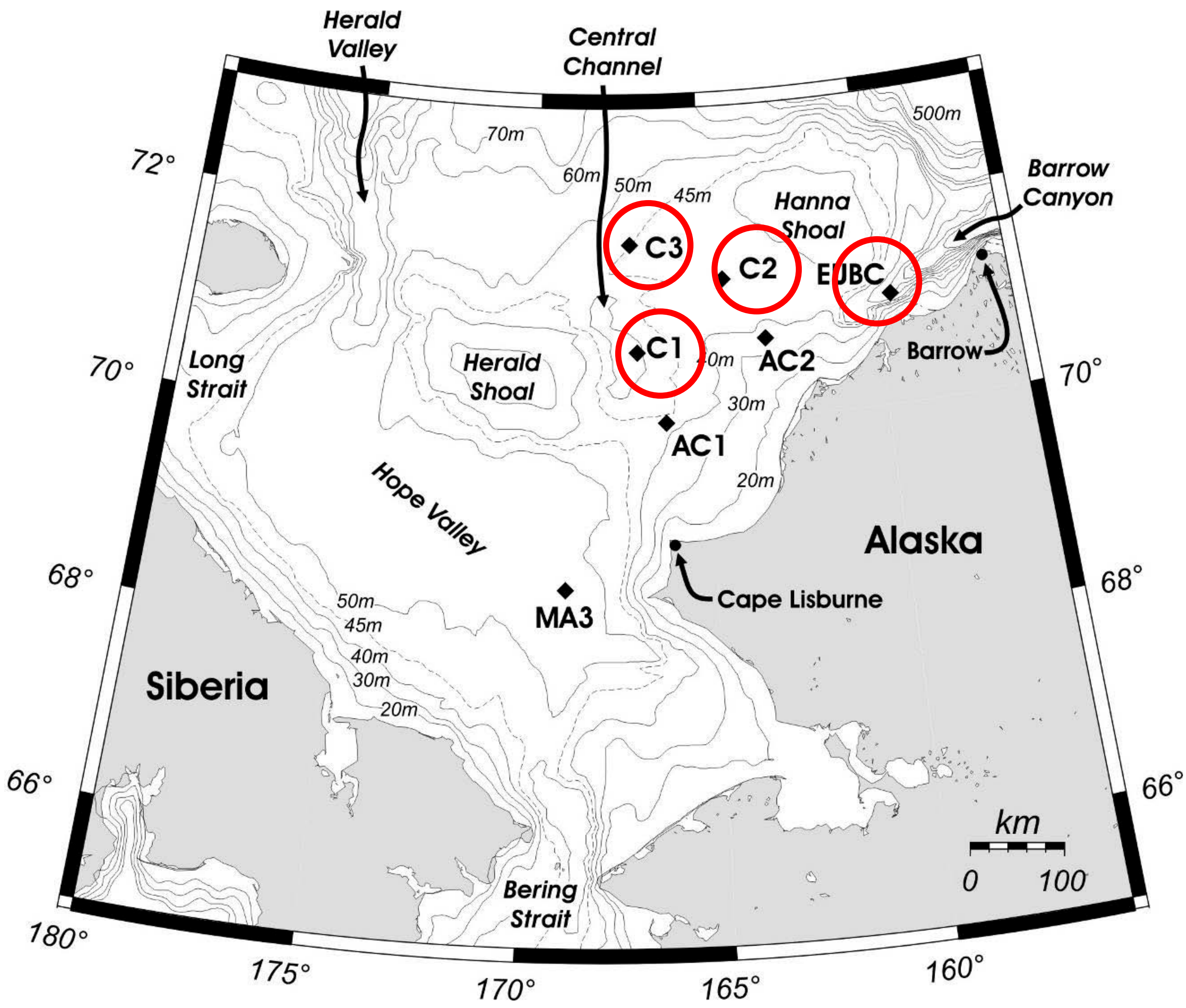
West-East Hydrographic Section

Bering Shelf "Summer Water"
T $\geq$ ~2C; 32 $\geq$ S $\leq$ 32.8

Ice Melt: T ~0C, S < 31

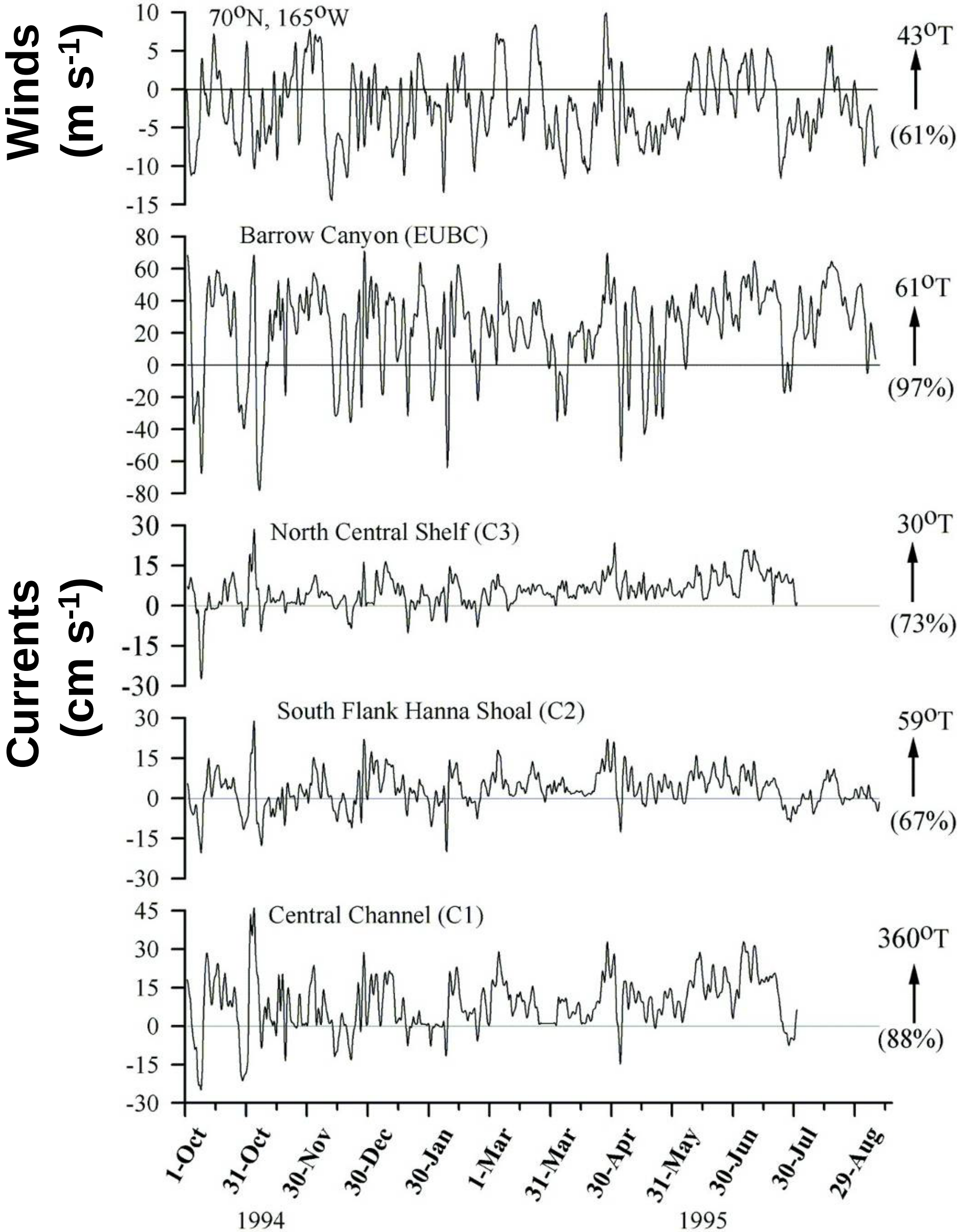
Shelf stratified from Spring through Fall.

Stratification varies spatially



Herald Valley
Central Channel
70m
500m
60m
50m
45m
Barrow Canyon
Hanna Shoal
72°
C3
C2
EJBC
C1
40m
AC2
Barrow
70°
Long Strait
Herald Shoal
30m
AC1
20m
Hope Valley
Alaska
68°
Cape Lisburne
MA3
50m
45m
40m
30m
20m
Siberia
66°
km
0
100
Bering Strait
180°
175°
170°
165°
160°

Circulation Variability



To NE

To SW

Subsurface current strength: proportional to bottom slope

~.5 m/s Barrow Canyon

~0.2 m/s Central Channel

~<0.1 m/s elsewhere

Wind-forced variability:

~50% of current variance

Coherence scales: ~300km (or more)

Currents fluctuate along-isobaths

Seasonal cycle:

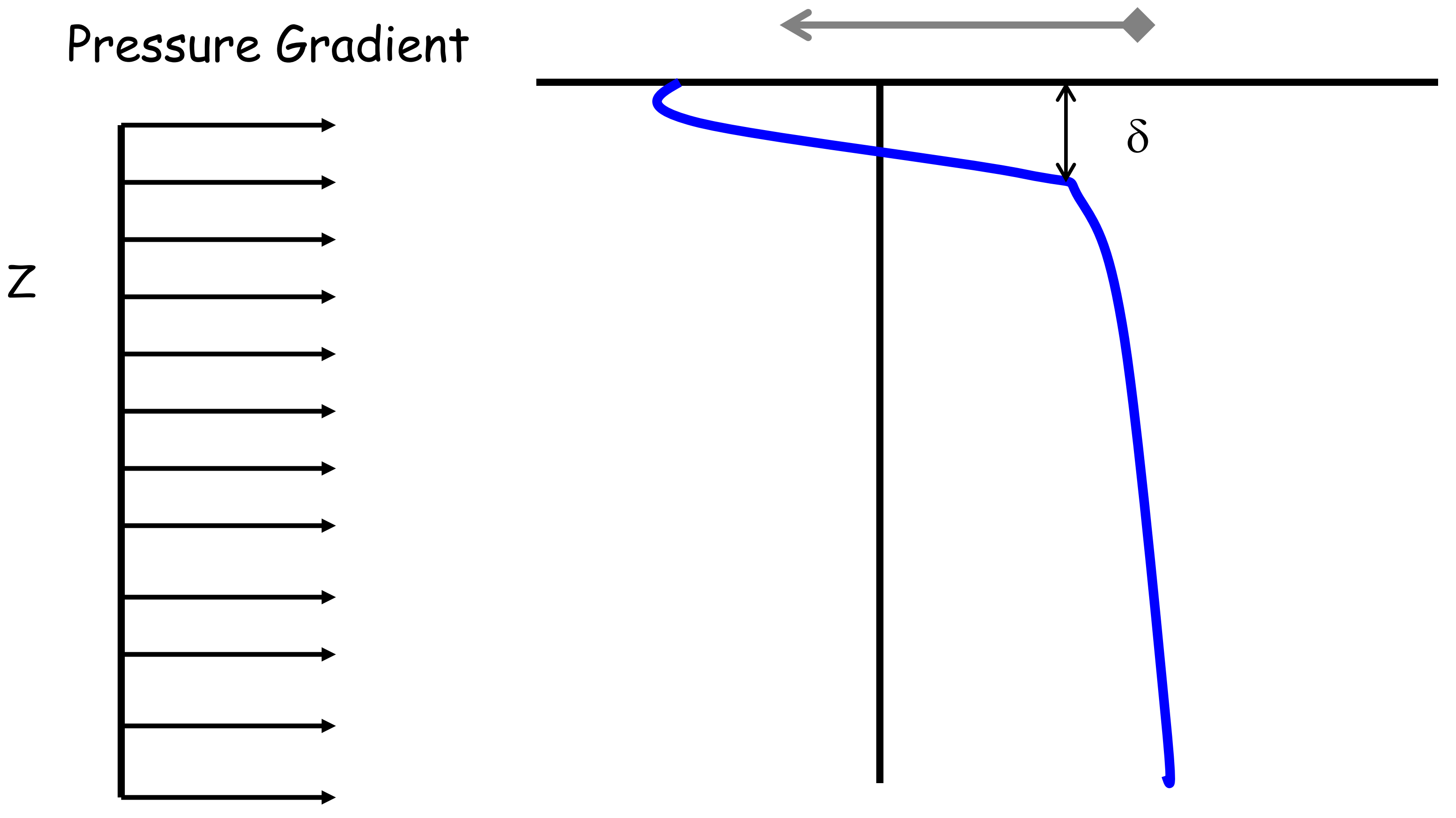
Winter: Max Variance

Summer: Min Variance

Why do the currents mostly oppose the winds?

δ= Depth over which wind stress modifies the velocity profile

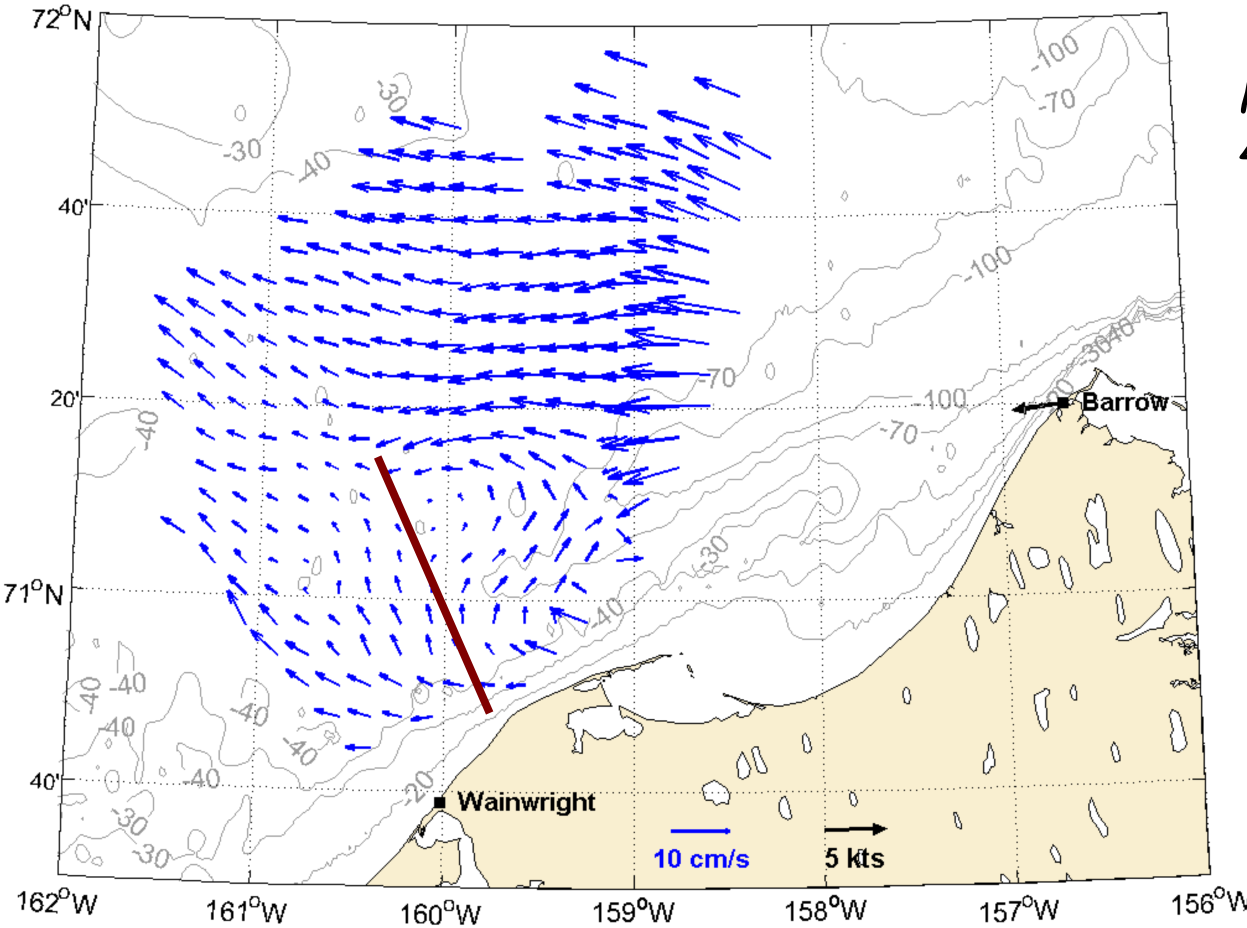
- depends upon wind strength, stratification, ice cover



How well do we know the surface circulation?

Sept. – Nov. 2009 Mean Surface Vectors

from Shore-based radars (Barrow and Wainwright)



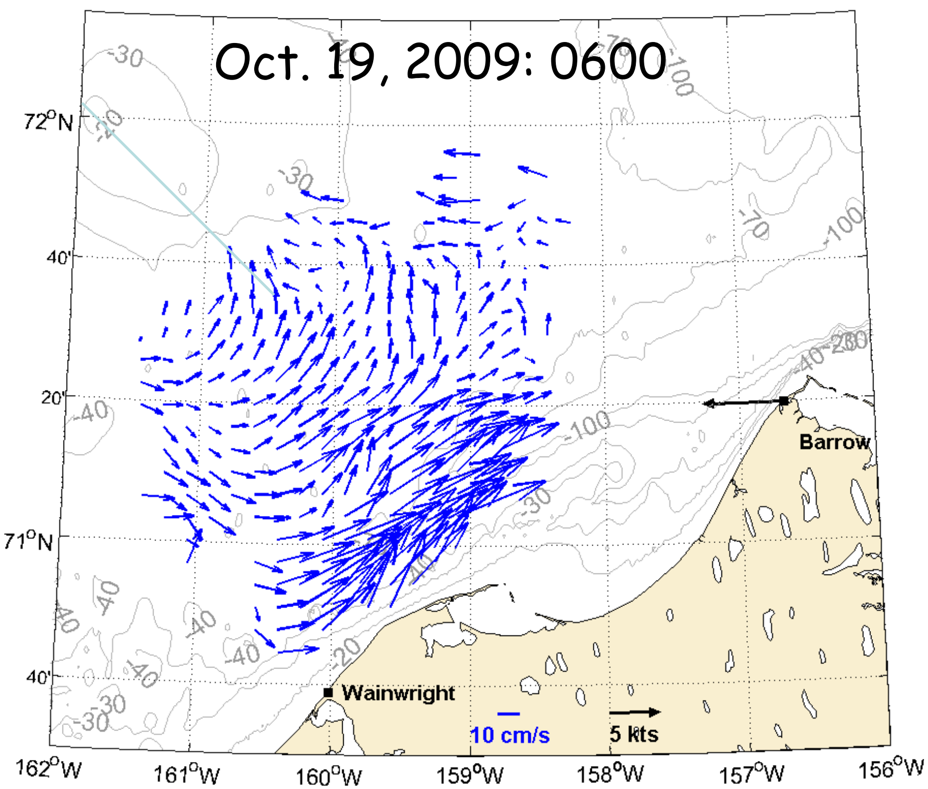
Mean Barrow Wind:
4.2 m s^{-1} toward 247^0

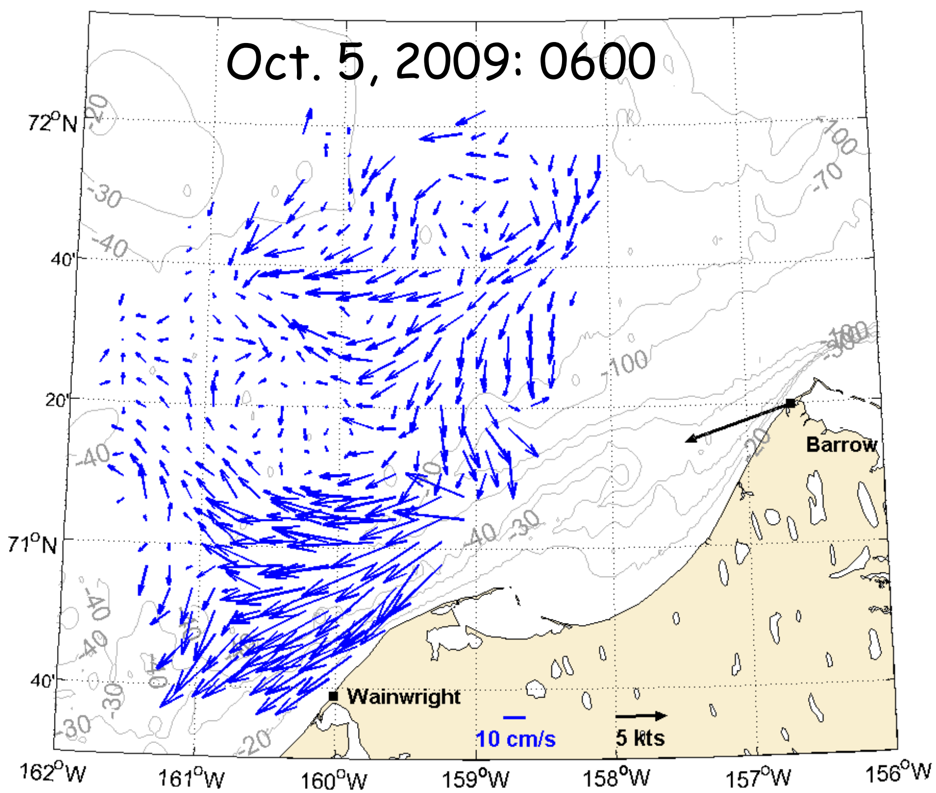
Mooring Array (deployed in 2010)

NO surface expression of the coastal current!!
e.g., winds oppose an alongshore pressure gradient

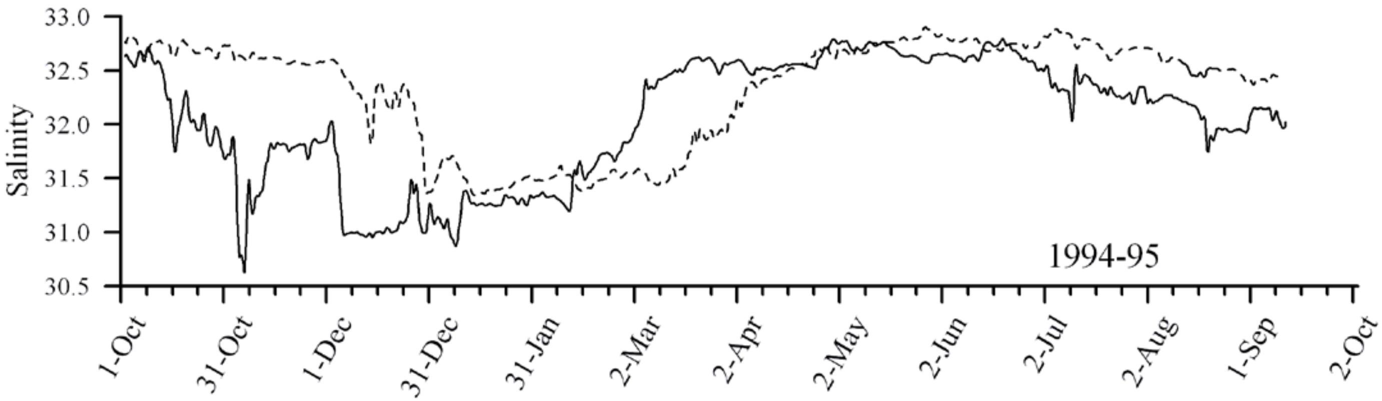
Weak (<15 kts) Westward winds
- NEward coastal jet
- 30 km width
- variable offshore

Moderately strong (15 kts) NE winds
- SWward coastal jet
- 30 km width
- variable offshore



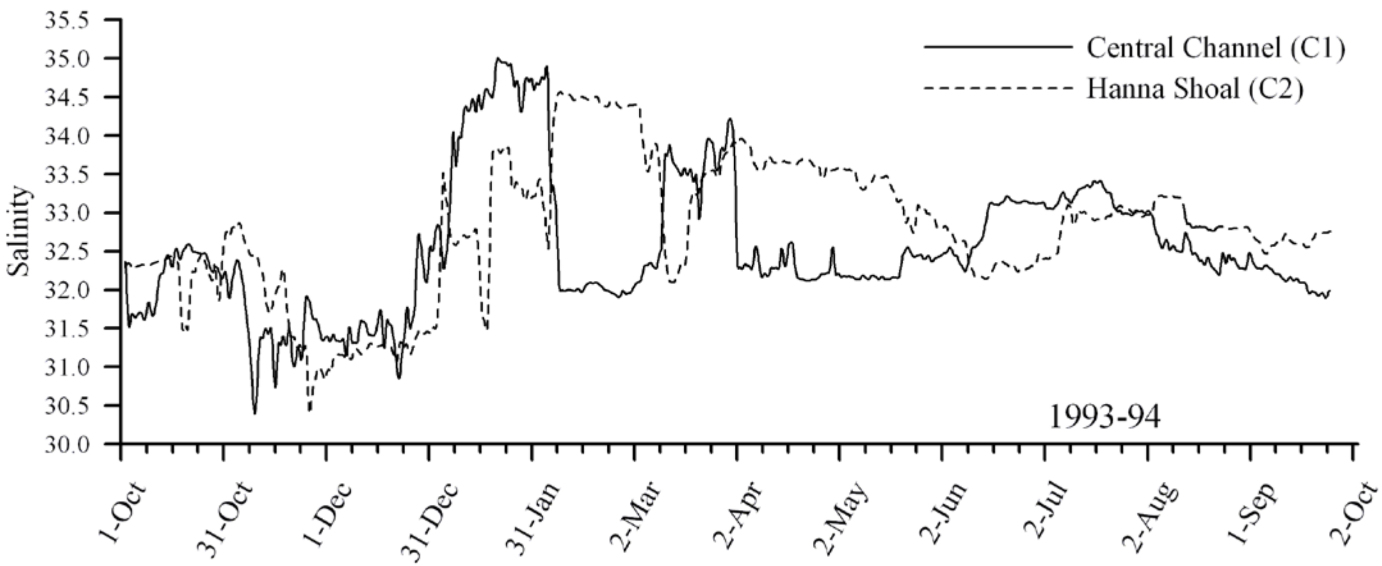


Water mass modification



NO MODIFICATION!

Heavy fall ice cover and few polynyas.
S varies per Bering Strait



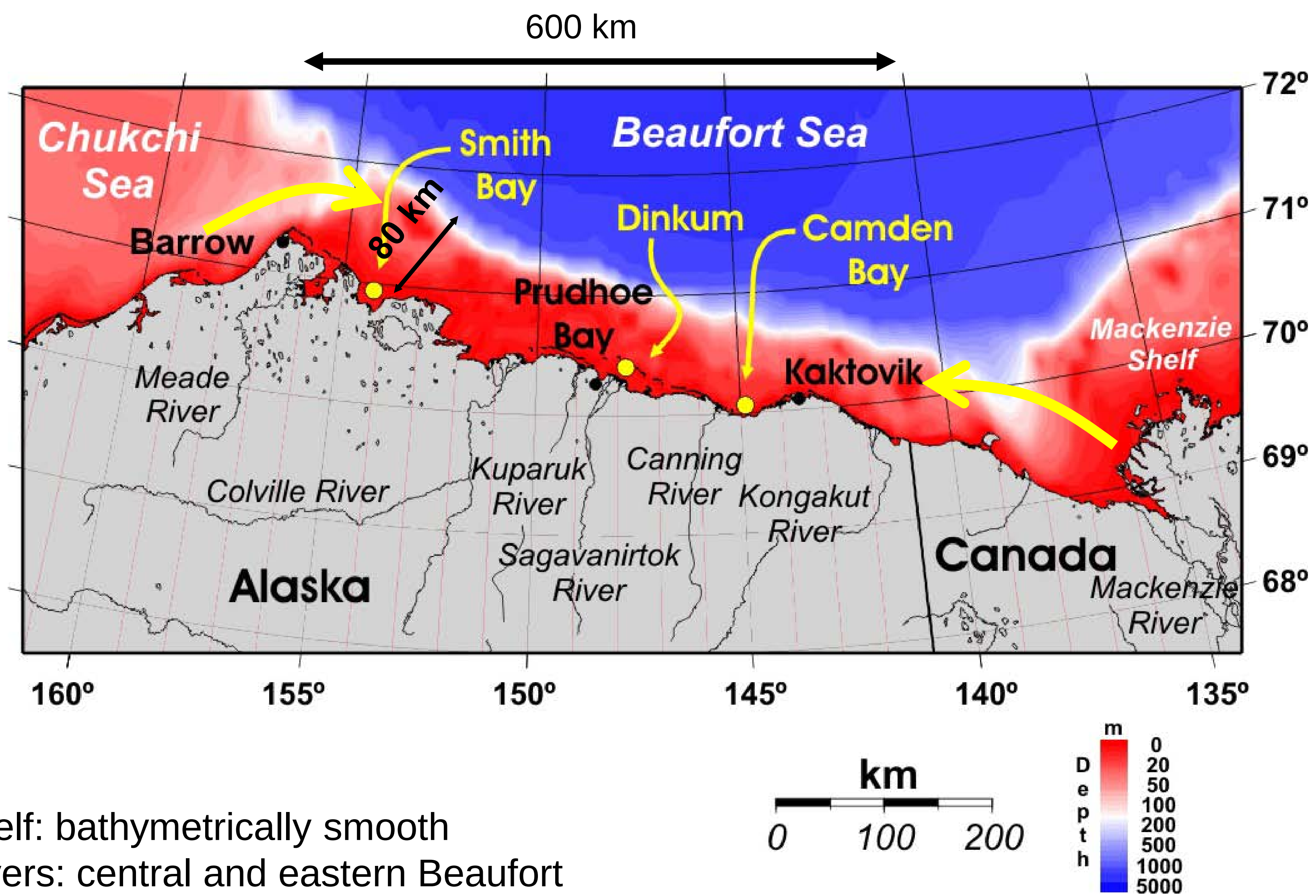
ACTIVE MODIFICATION!

"light" fall ice and large polynyas
S-enhancement due to ice production

The Alaskan Beaufort Shelf

Properties and Dynamics are set by:

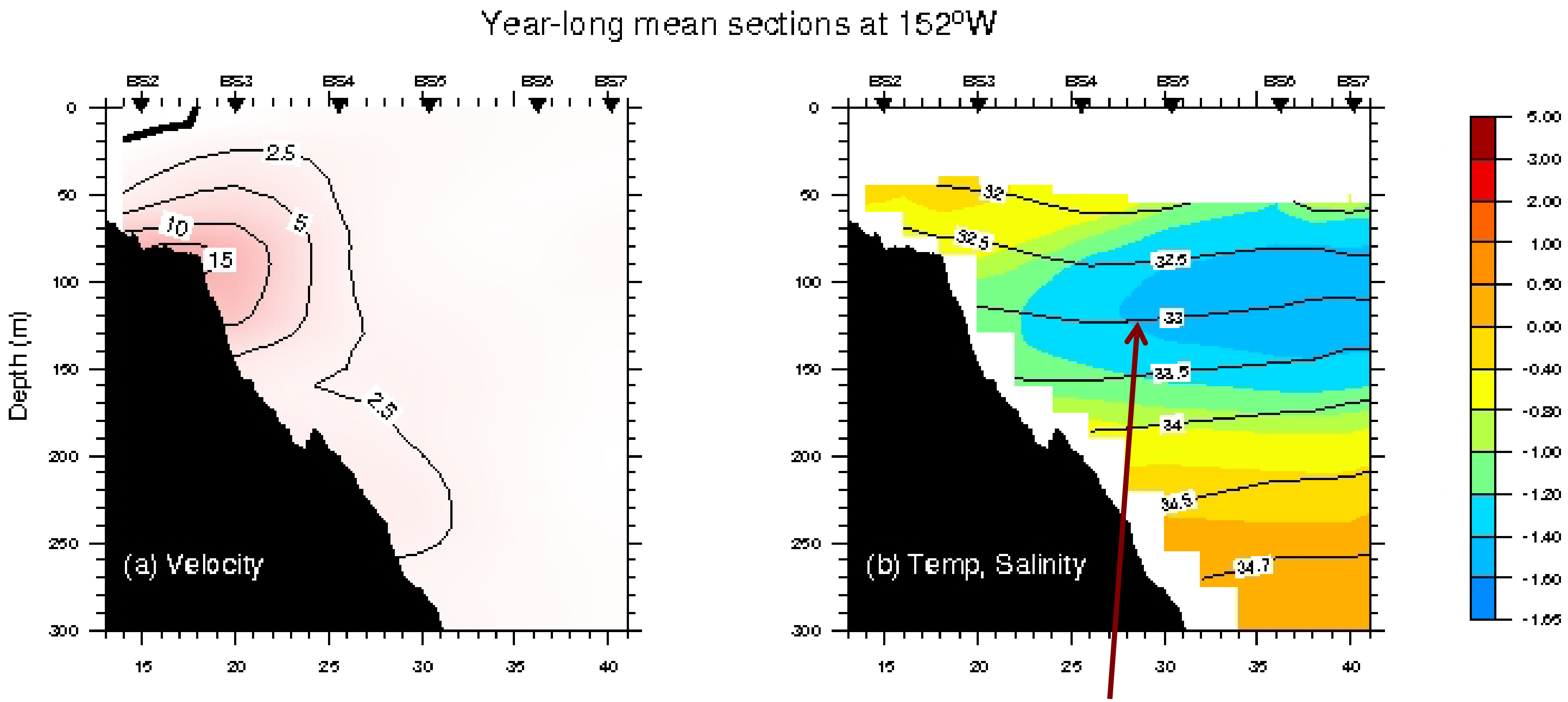
1. Lateral, oceanic (shelfbreak), and coastal boundaries
2. Freeze/thaw cycle



Shelf: bathymetrically smooth

Rivers: central and eastern Beaufort

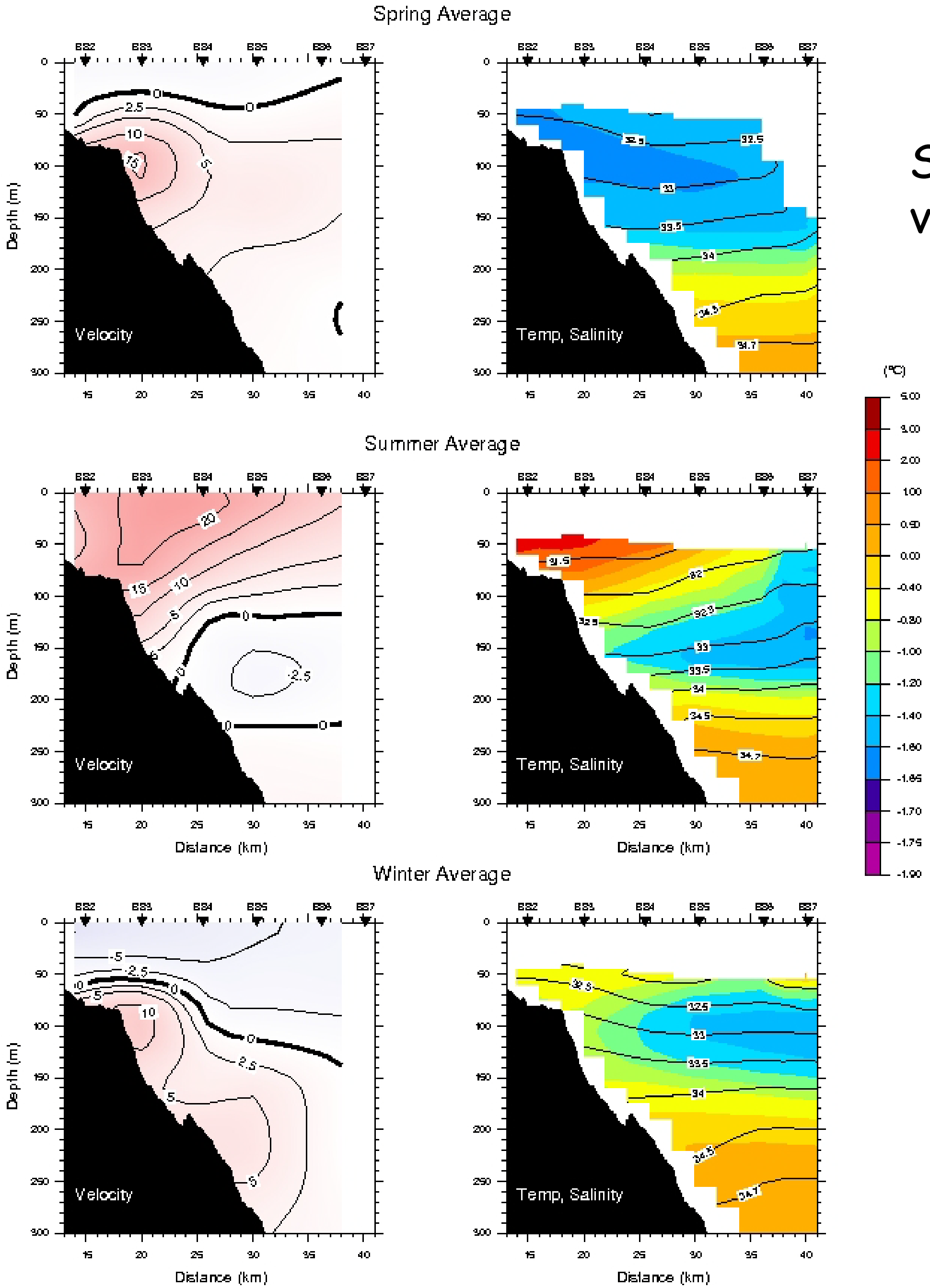
The Oceanic Boundary
Shelfbreak controls shelf/basin exchange



Mean eastward flow within the cold upper halocline:

- centered at ~100m; 15 km wide
- includes "Chukchi winter water" (T < -1C; 32.5 < S < 33.5)

(courtesy R. Pickart)



Shelfbreak current & density structure varies seasonally:

affects exchange via:

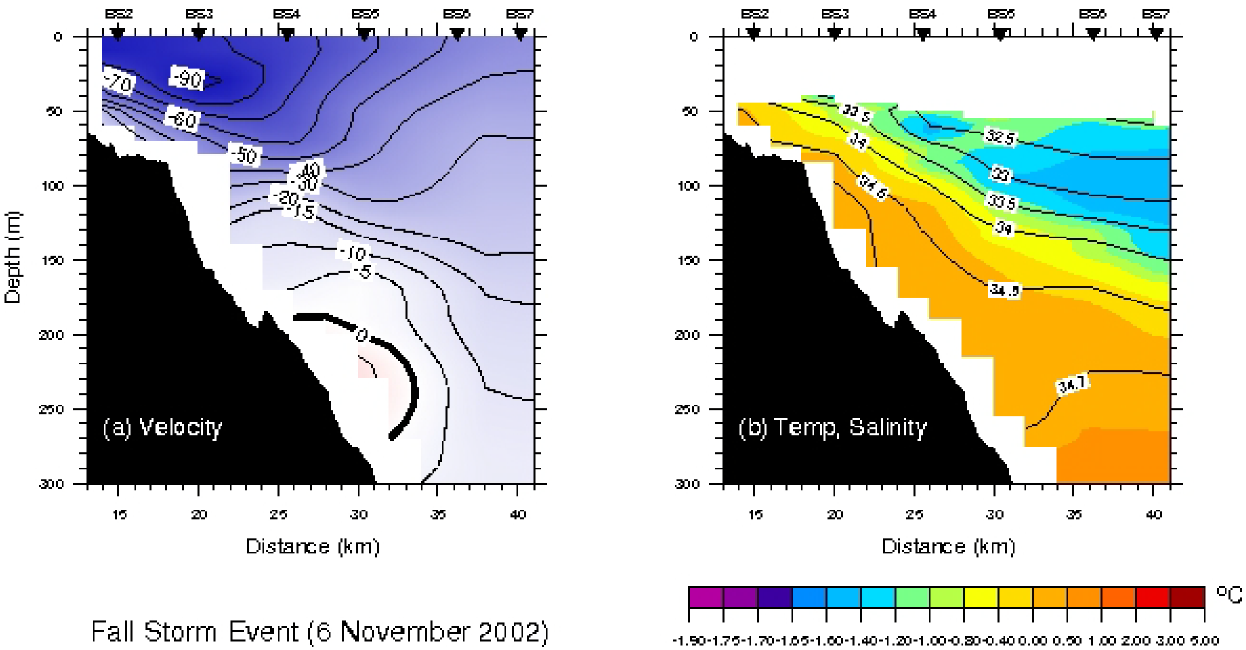
eddy generation

up/downwelling response

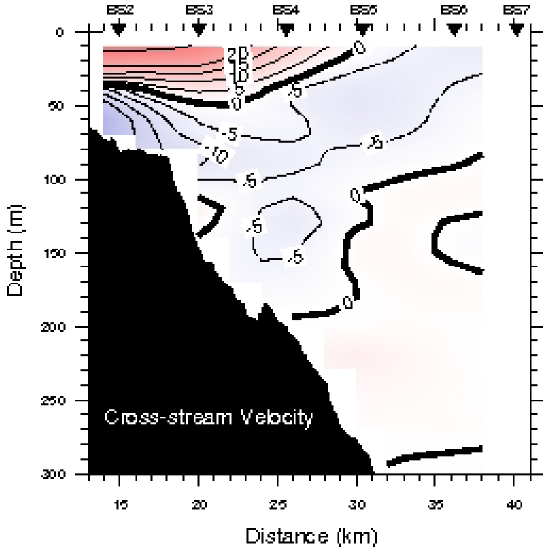
(courtesy R. Pickart)

Shelfbreak Upwelling Event

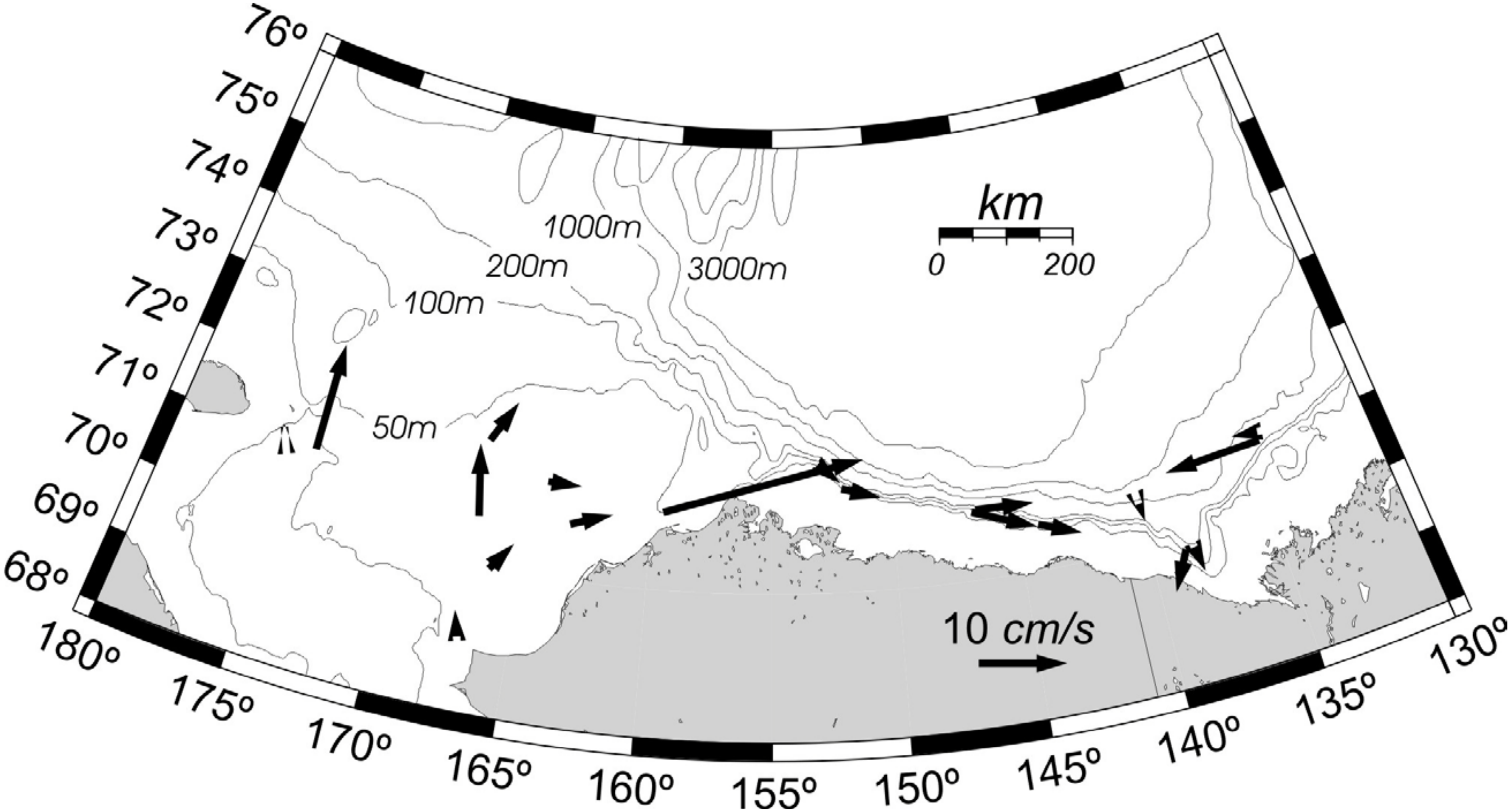
Fall Storm Event (6 November 2002)



Fall Storm Event (6 November 2002)

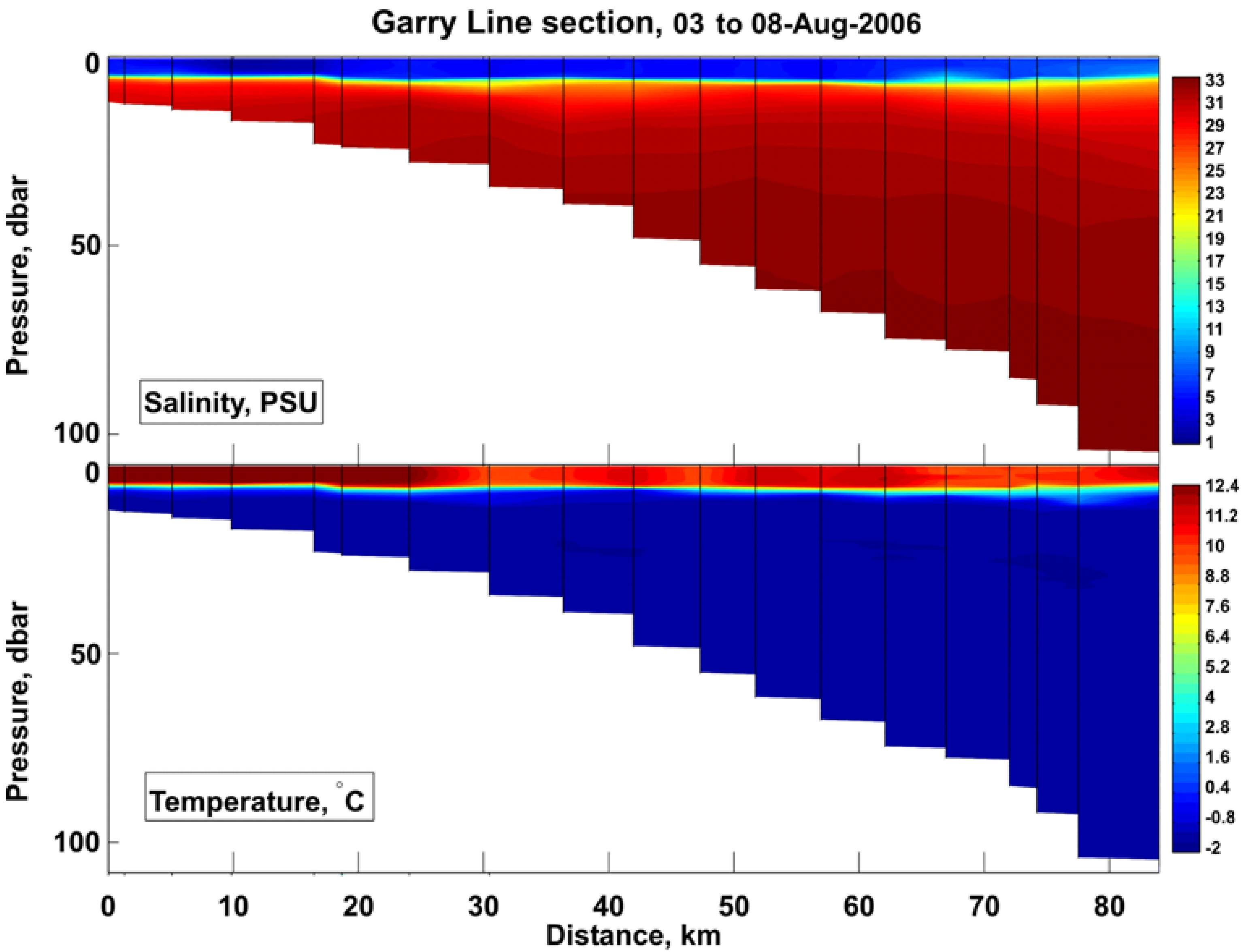


(courtesy R. Pickart)

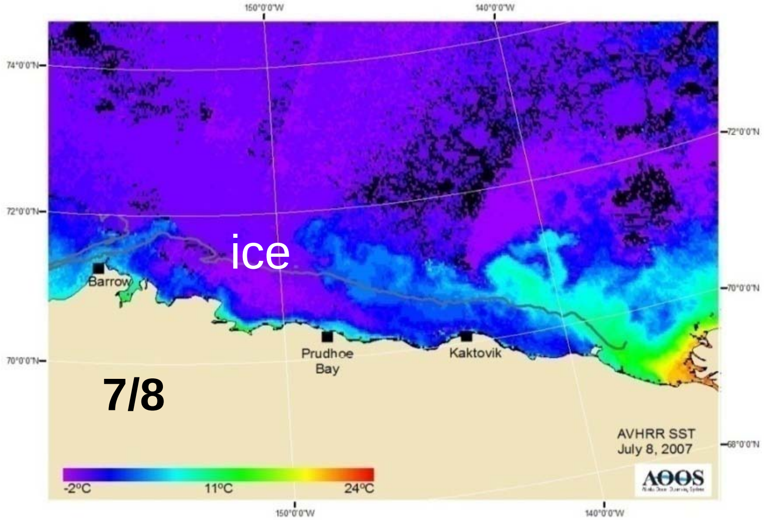


Shelfbreak jet has connections to the Chukchi Shelf, but how does it vary downstream?

Eastern Beaufort Shelf: the Mackenzie Influence



(courtesy W. Williams, DFO)



July 2007

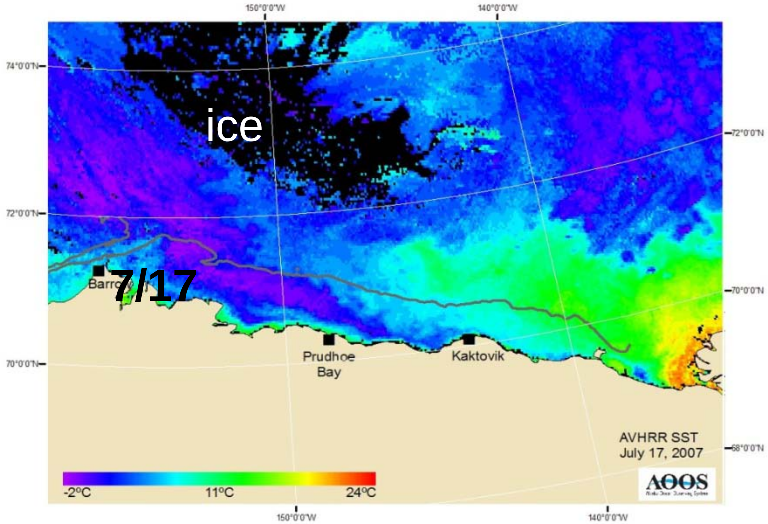
Plume Spreading Speed: 8 cm/s

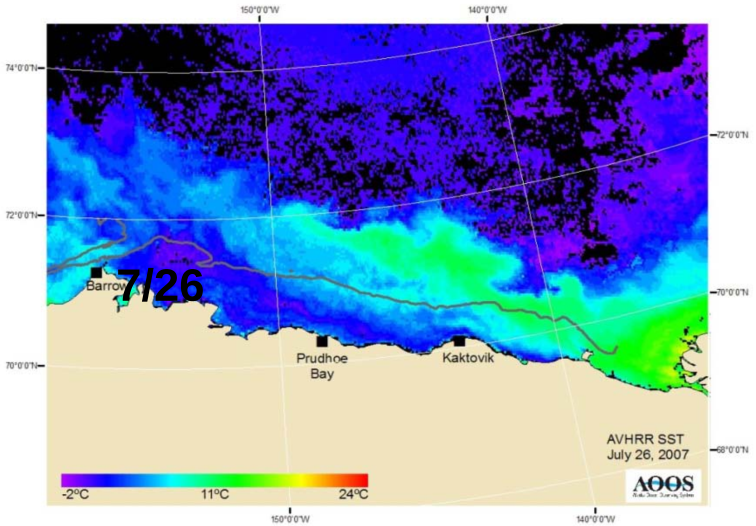
Heat Flux: ~100 Wm^{-2} (2.5cm d^{-1})

Solar Radiation: ~200 W m^{-2}

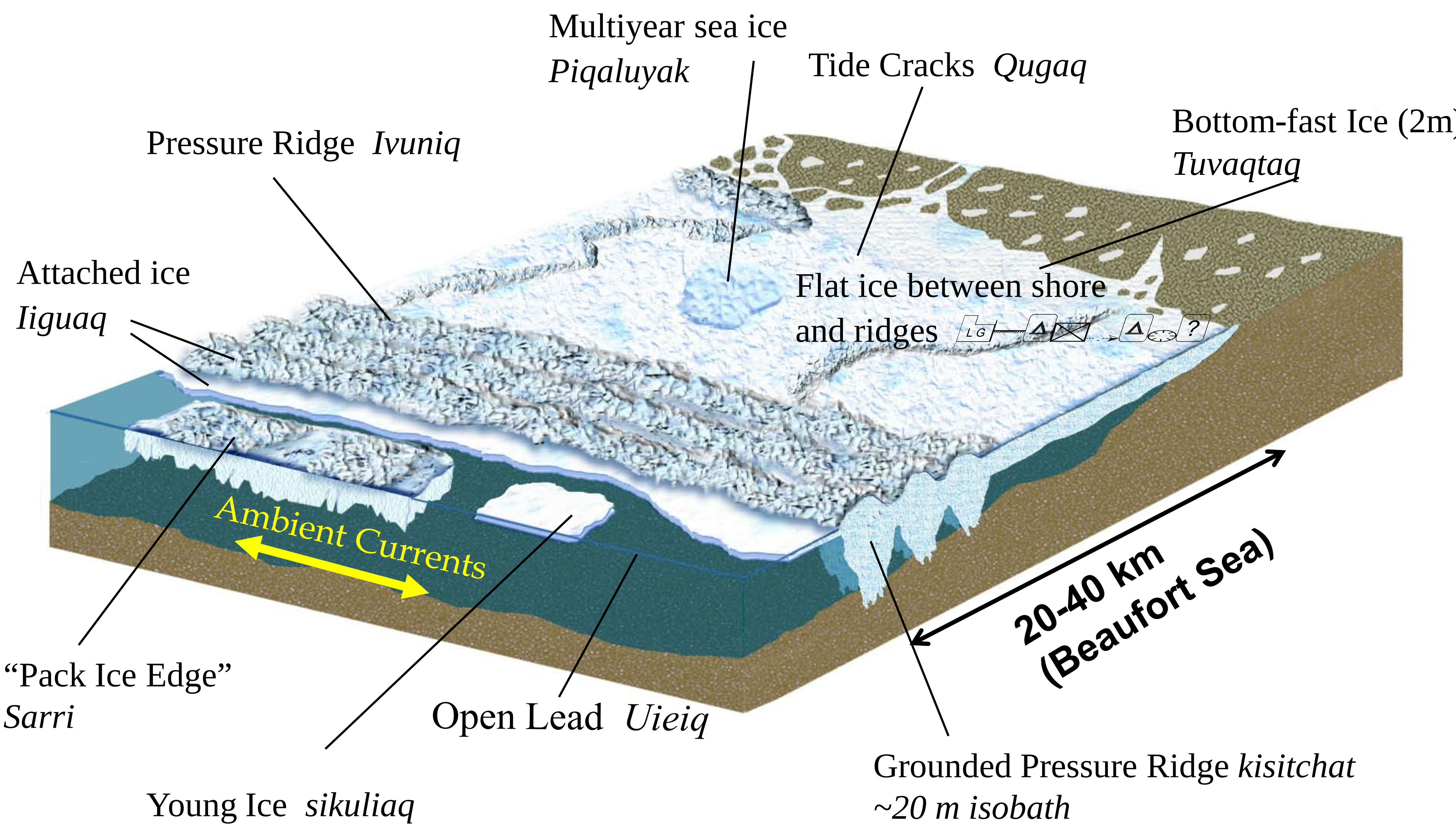
Important in ice retreat

E-W property differences



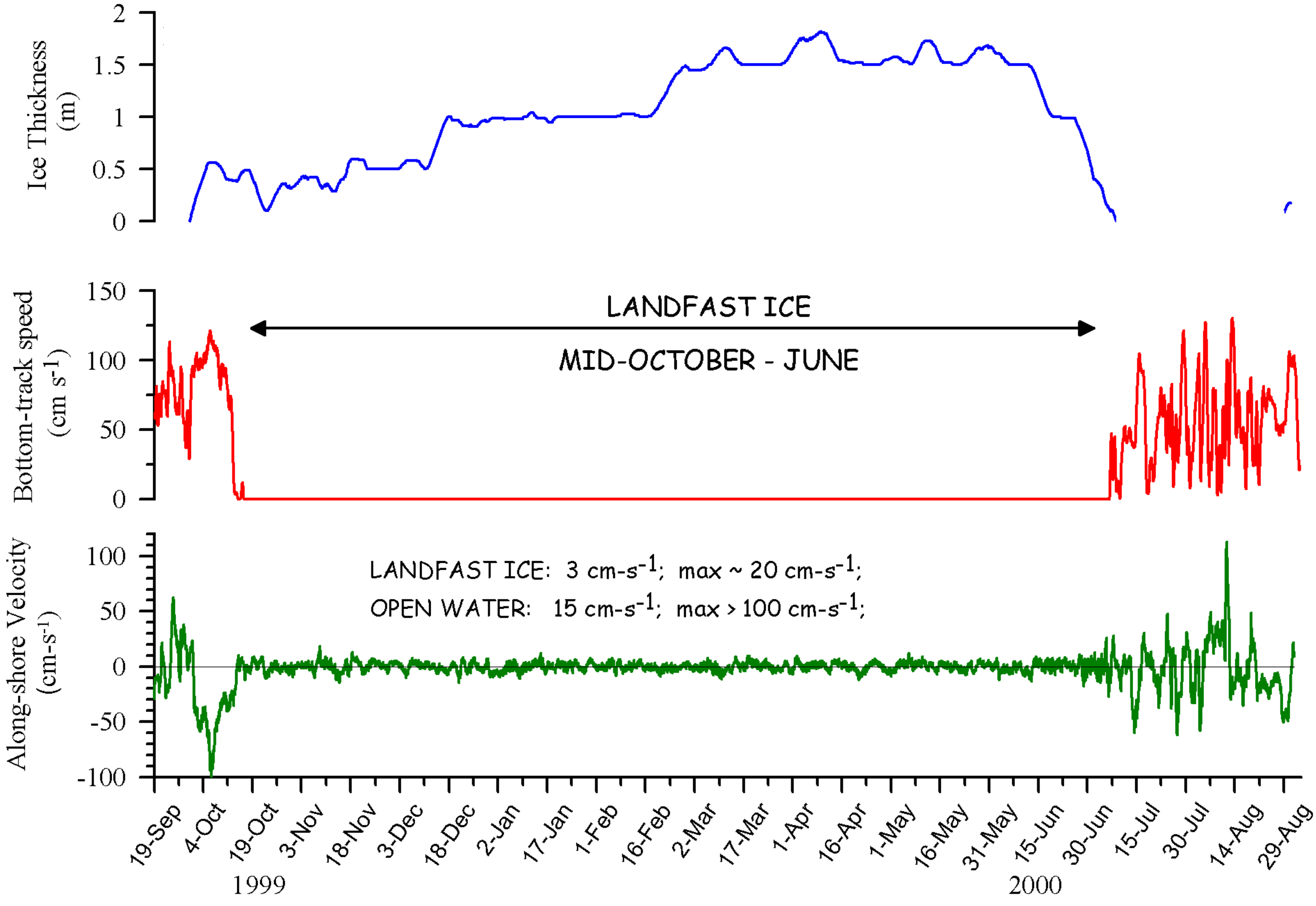


Landfast ice – occupies 20% of shelf

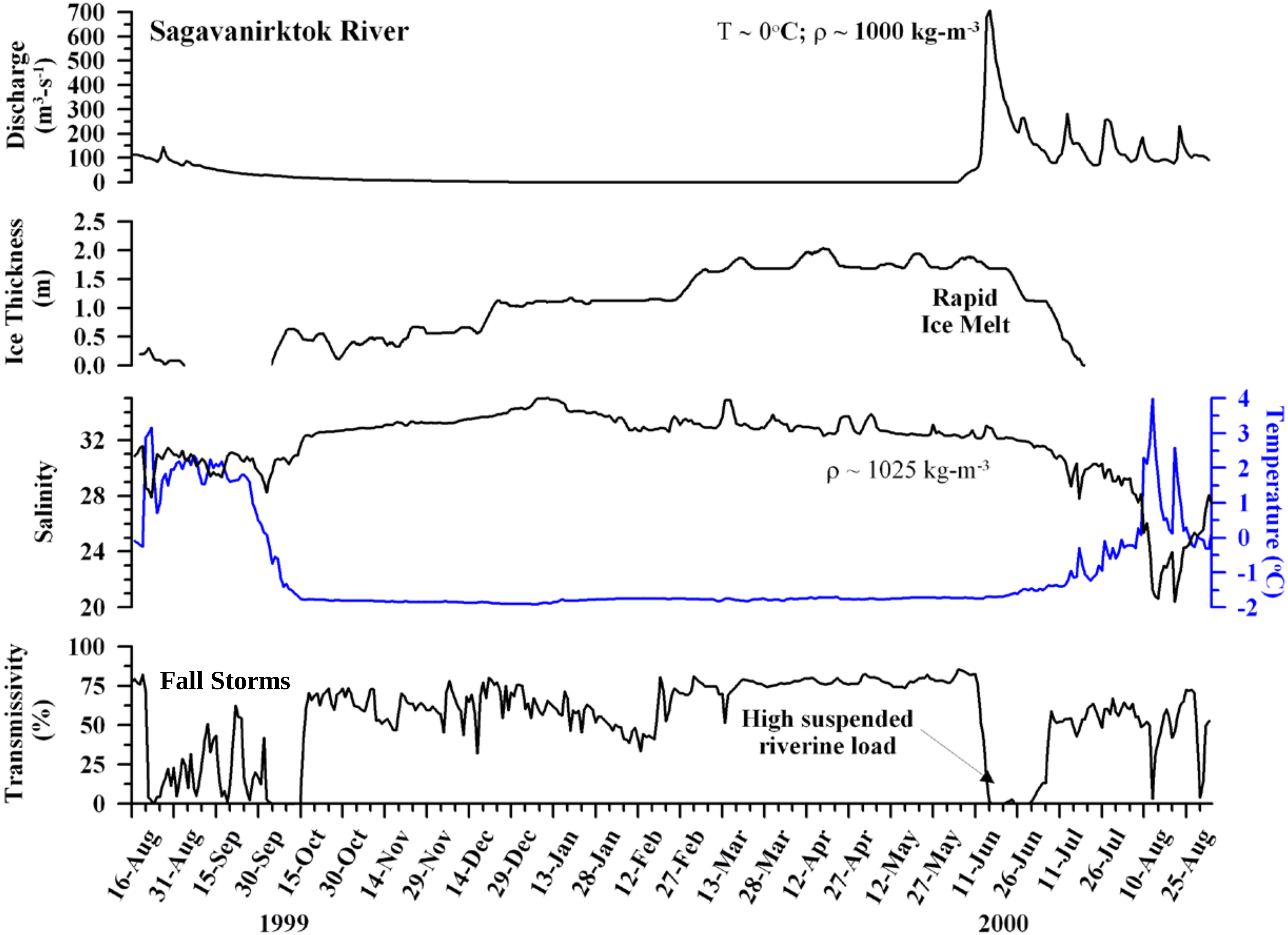


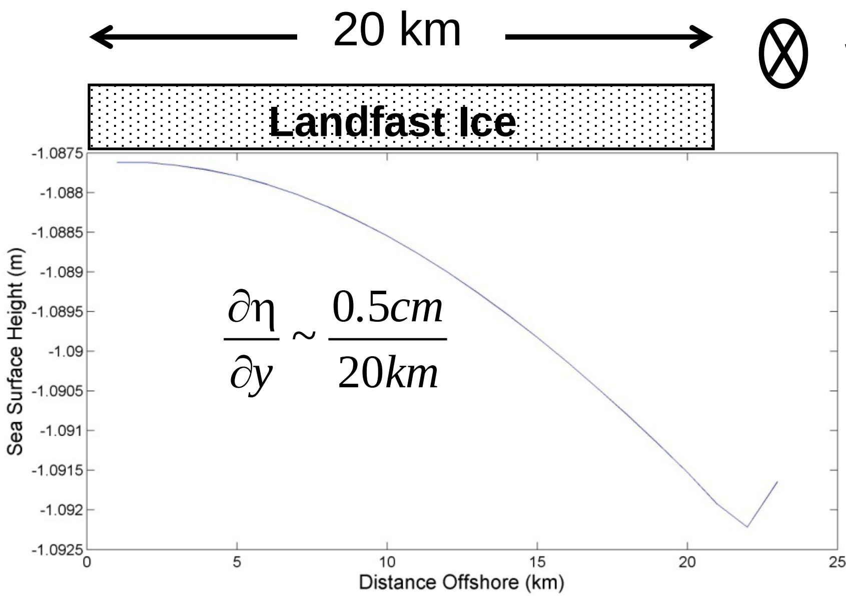
(Craig George, pers. comm.)

The Annual Cycle: Ice Thickness, Ice Set-up & Alongshore Currents



Annual cycles: river runoff, ice, temperature, salinity, transmissivity

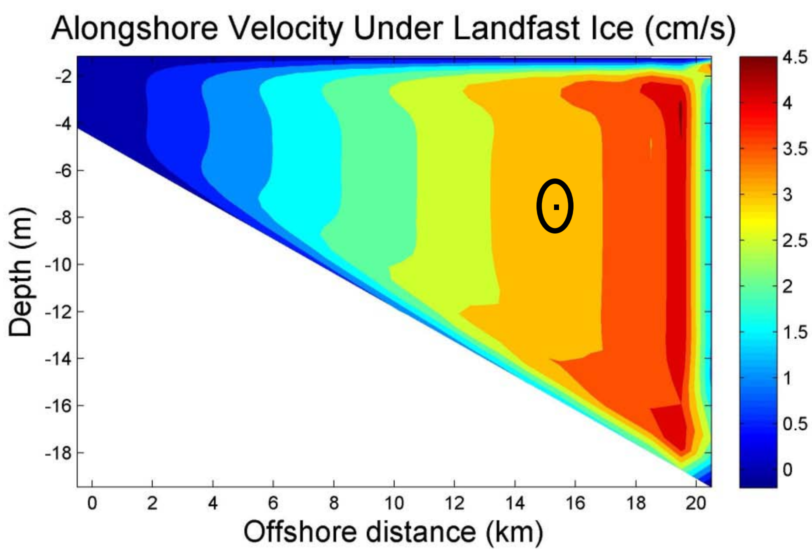


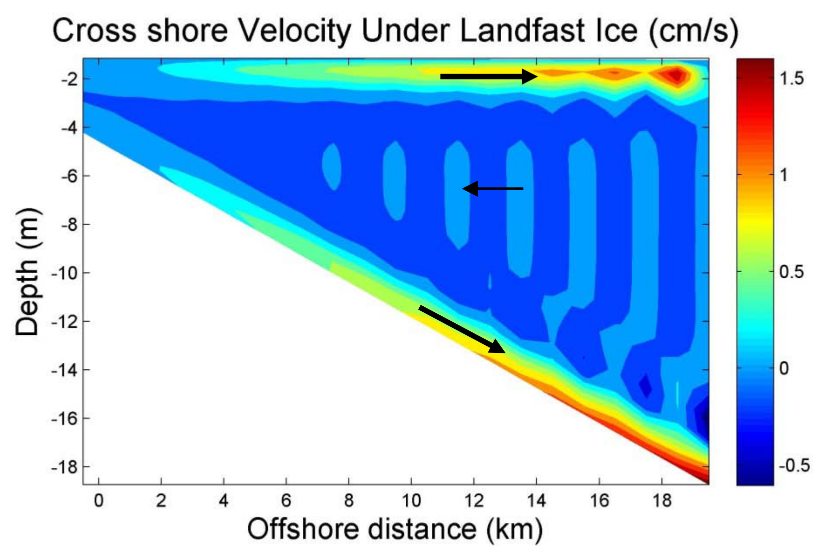


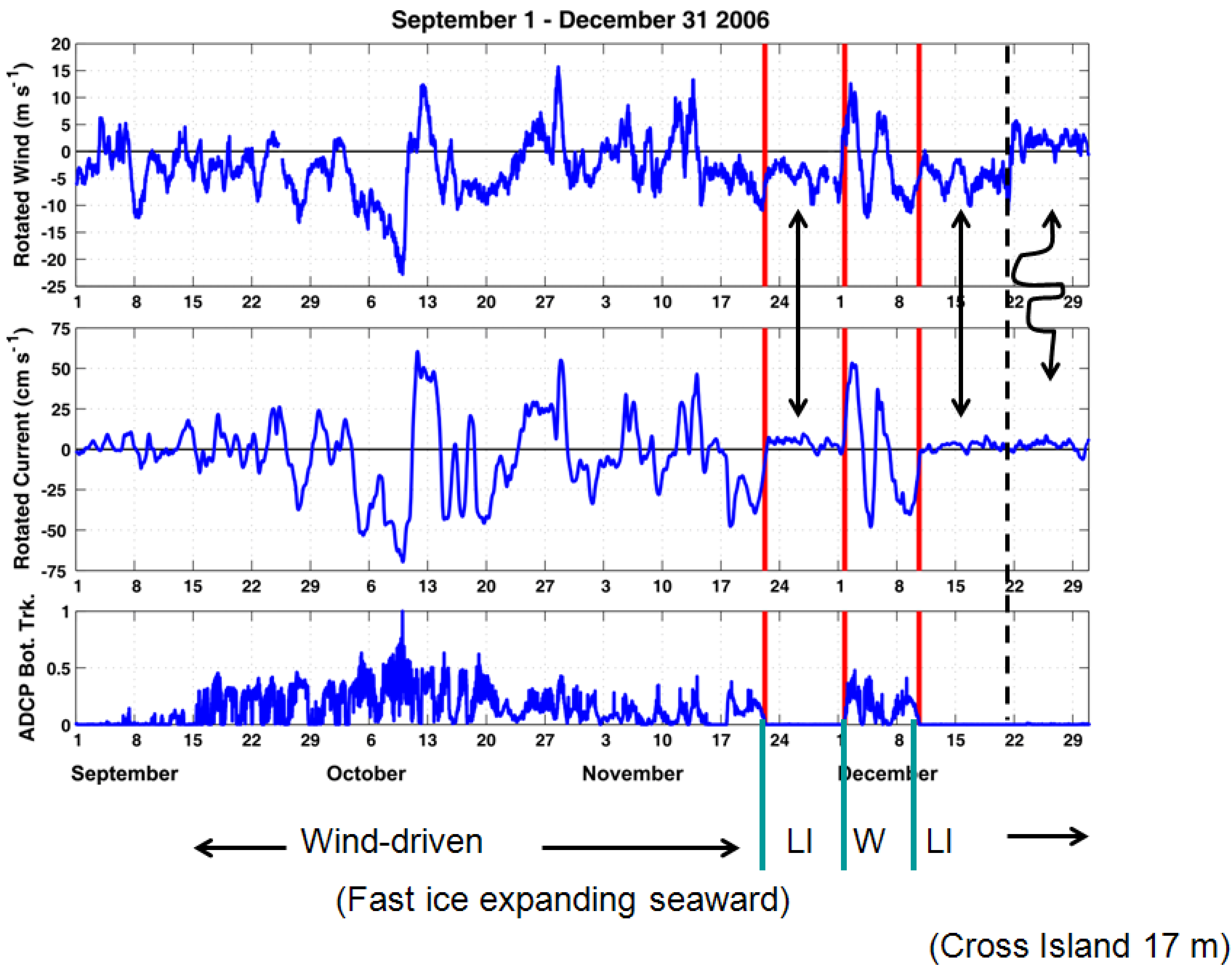
West wind
7 m s^{-1}

Near Steady 3-D Model
constant ρ
$r_i = r_b = 10^{-4}$ m s^{-1}
bottom slope: 10^{-3} (ABS)

Offshore: ice-edge jet (not shown)
Weak underice currents: **upwind**






September 1 - December 31 2006
Rotated Wind (m s⁻¹)
Rotated Current (cm s⁻¹)
ADCP Bot. Trk.
September
October
November
December
Wind-driven
LI
W
LI
(Fast ice expanding seaward)
(Cross Island 17 m)

"Open water"/ "drifting ice" currents"

15 (100 cm-s^{-1} max)

Alongshore coherence scales ~300 km

Correlated with winds

Landfast Ice Winter Currents:

~5 cm-s^{-1},

Alongshore coherence scales: ~100 km,

Uncorrelated with local or remote winds.

Why?

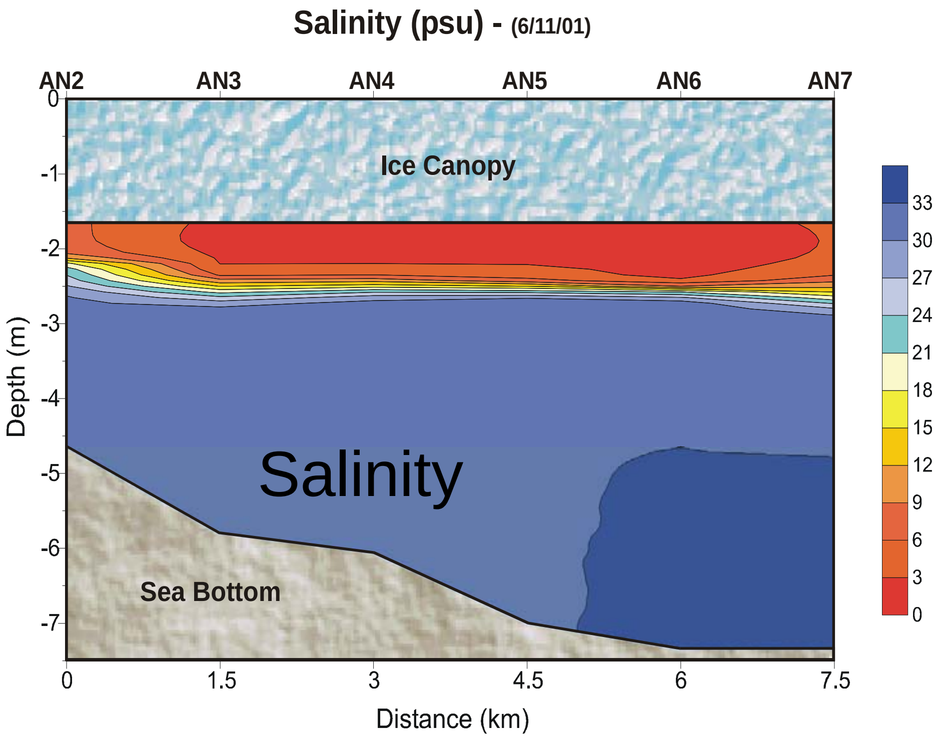
Spatial variations in r_{ice} (due to underice topography) and/or

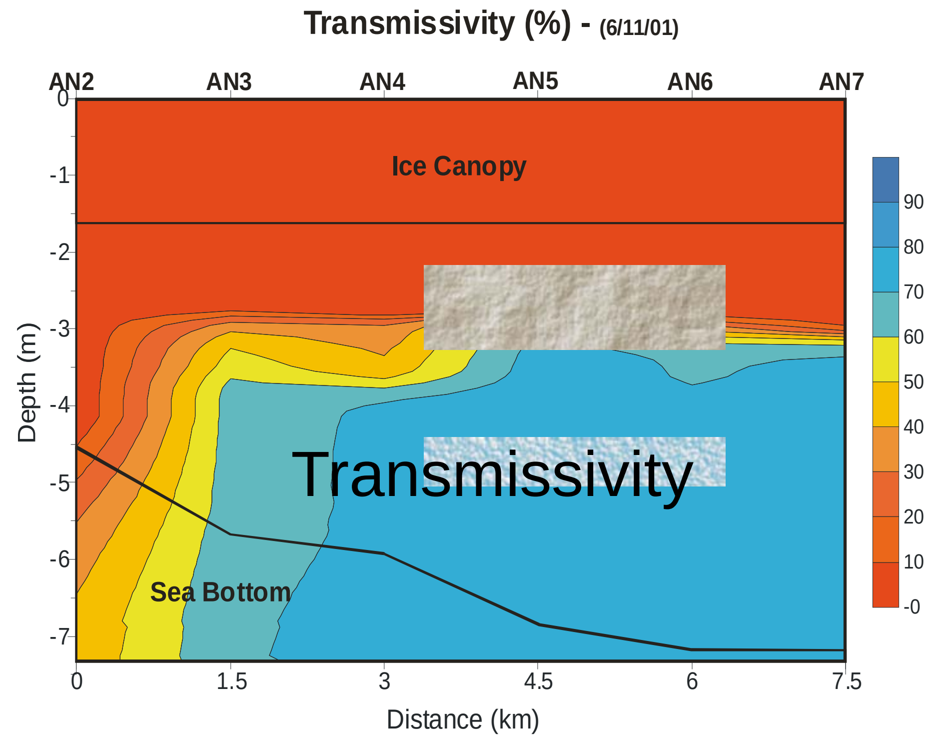
Alongshore variations in landfast ice width

- adjust along-shore pressure field and
- small along-shore correlation scales

r_{ice} and ice width are related to landfast ice dynamics

Under-Ice Plumes: The shelf is the estuary!!

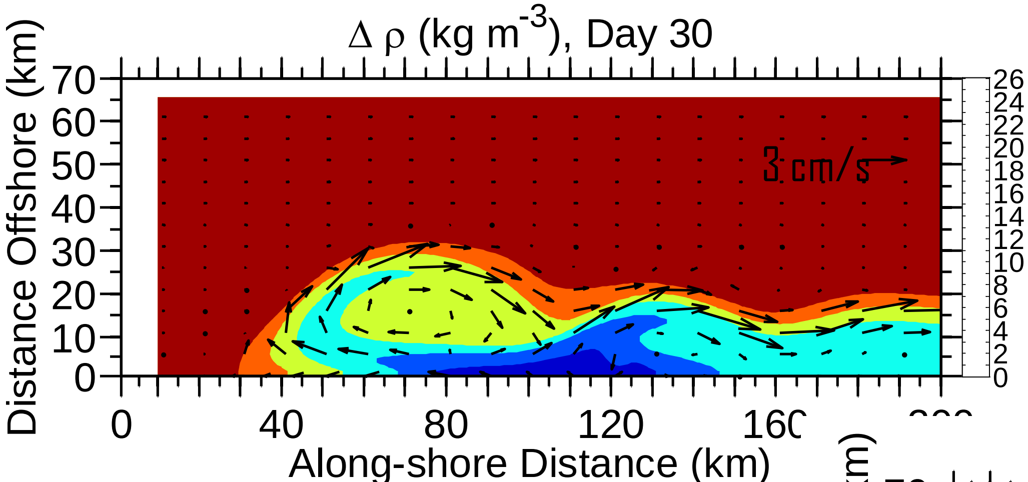




Highly stratified: Ri # ~320.

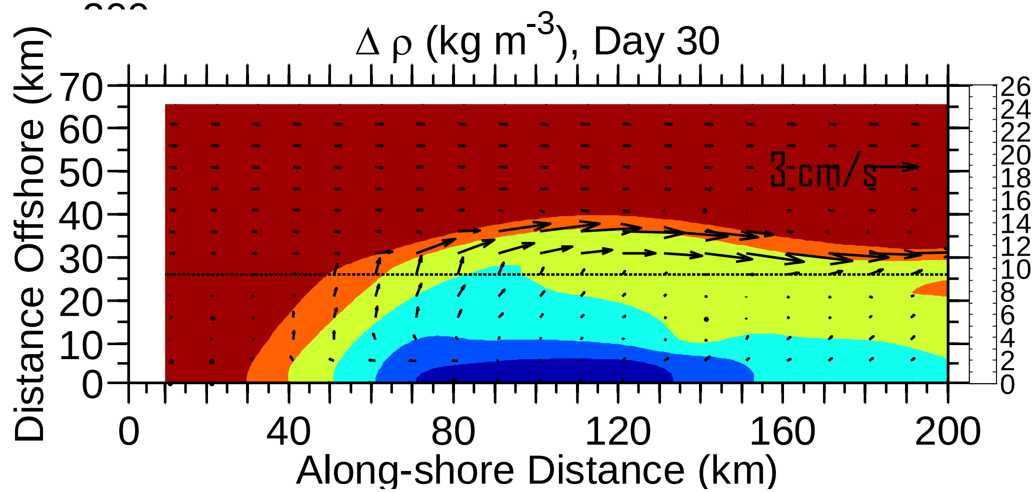
Mixing inhibited – no direct wind forcing and tides are weak: ~2 cm/s.

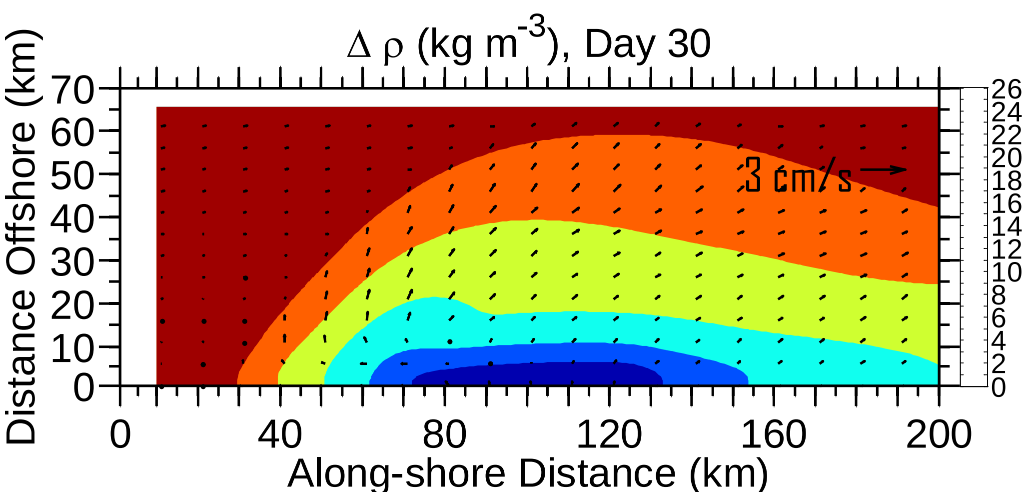
Plume Spreading is altered in the presence of landfast ice



No ice

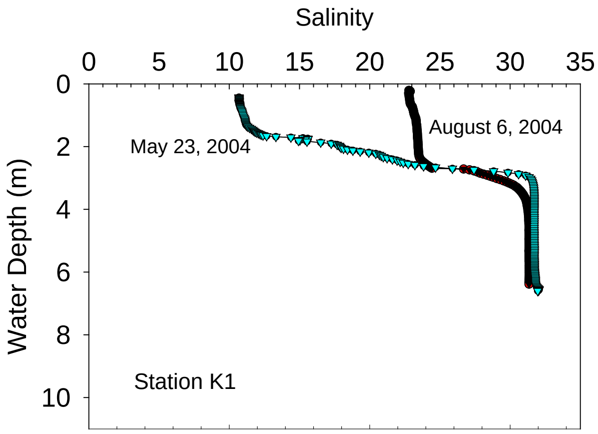
Partial ice





Total ice

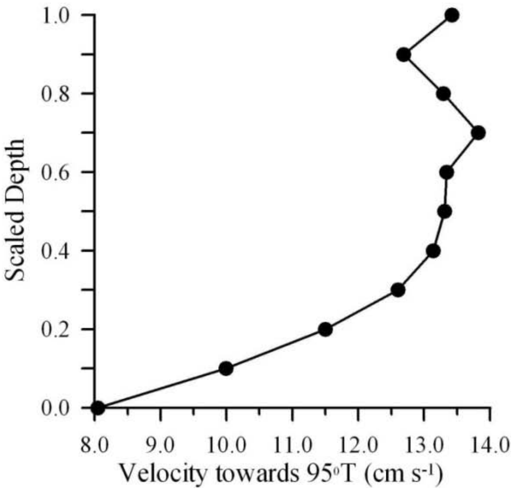
(Kasper and Weingartner, in prep.)



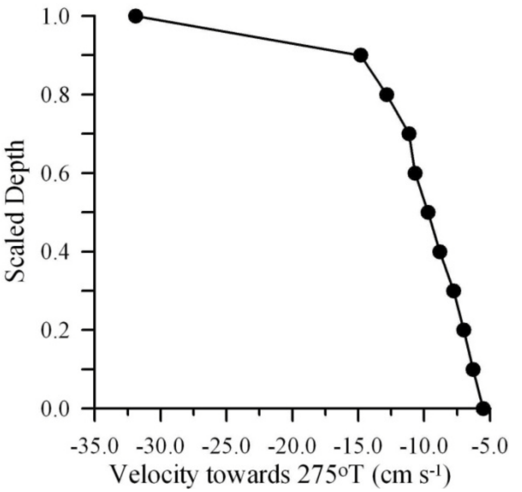
(J. Trefey; pers. comm.)

Mean Jul-Aug Current profiles
Along-shore

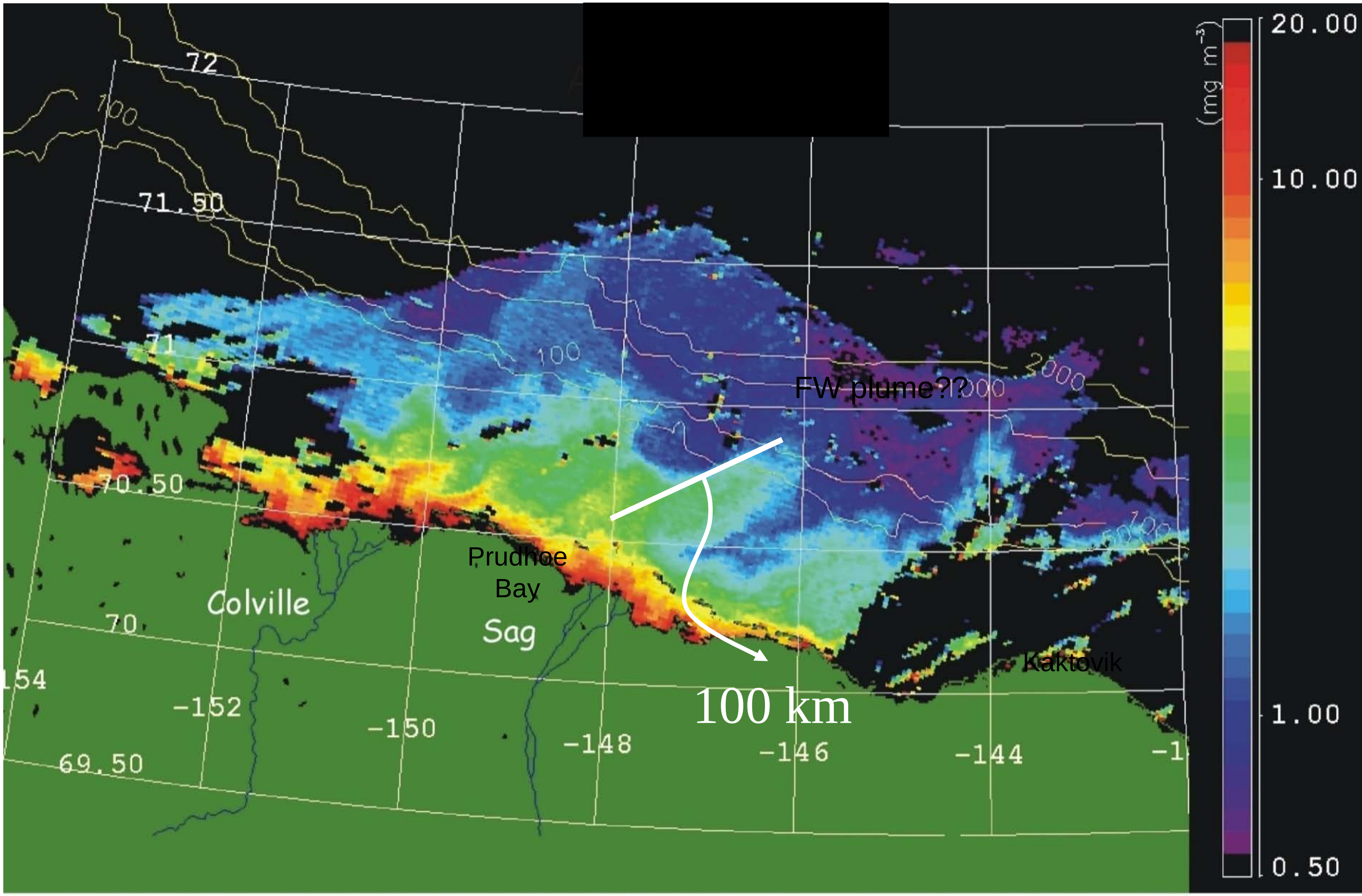
Downwelling
(plume mixes, small shear)



Upwelling
(highly stratified; large surface shear)



Upwelling fronts may be unstable

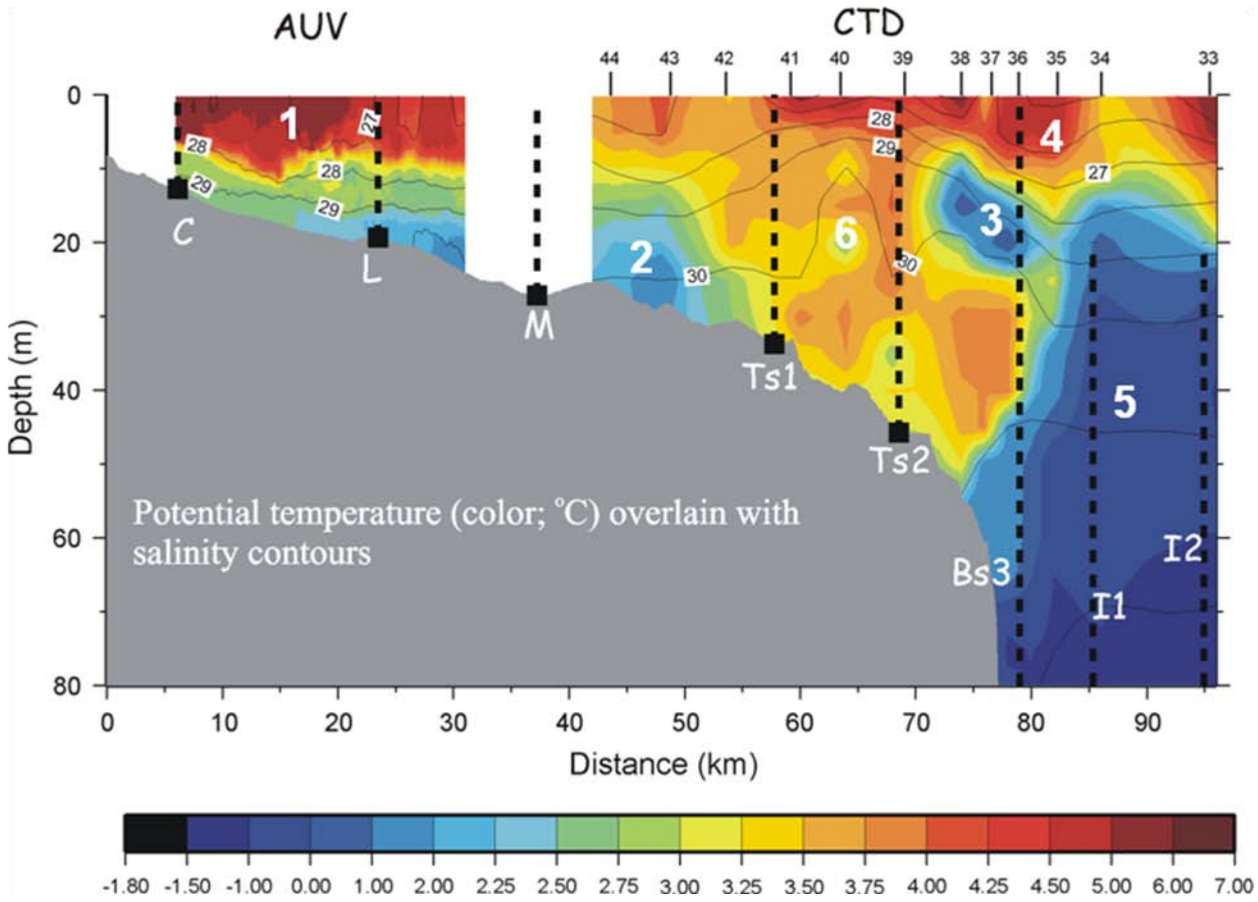


Winds (preceding 7 days): Variable 5 - 10 m/s

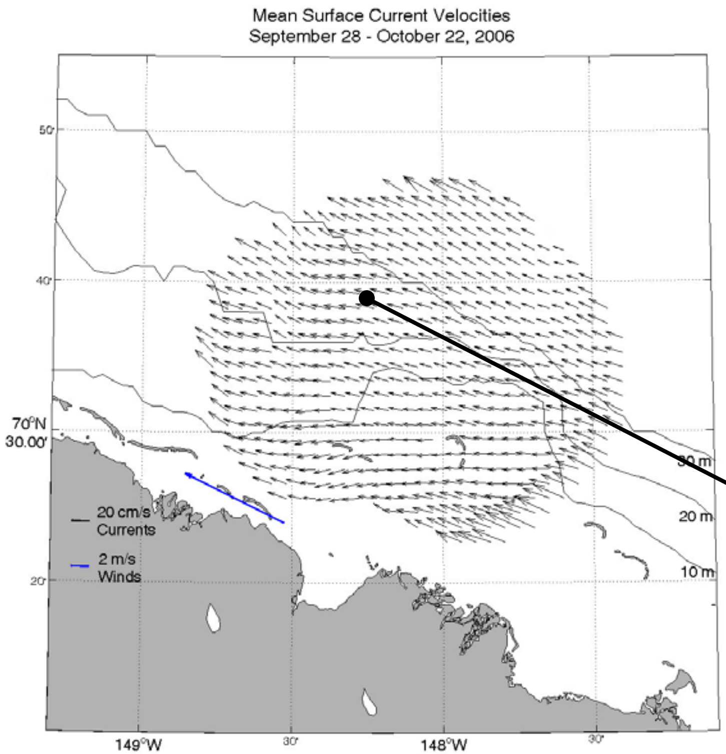
(Courtesy, M. Schmidt)

Summer/early fall reflects boundary forcings:

1. warm, fresh, Colville River plume (***coastal boundary***)
2. mid-shelf cold pool, remnant of winter or shelfbreak upwelling event (***western and/or oceanic boundary***);
3. shelfbreak eddy; Chukchi winter water (***oceanic boundary***);
4. Mackenzie River plume filament spreading westward (***eastern boundary***);
5. cold Chukchi winter water (***western + oceanic boundary***);
6. warmer Chukchi summer water (***western boundary***)



Fall is the wind season (Sep – Oct): Strong winds, well-mixed(?) conditions



12 MHz HF radar

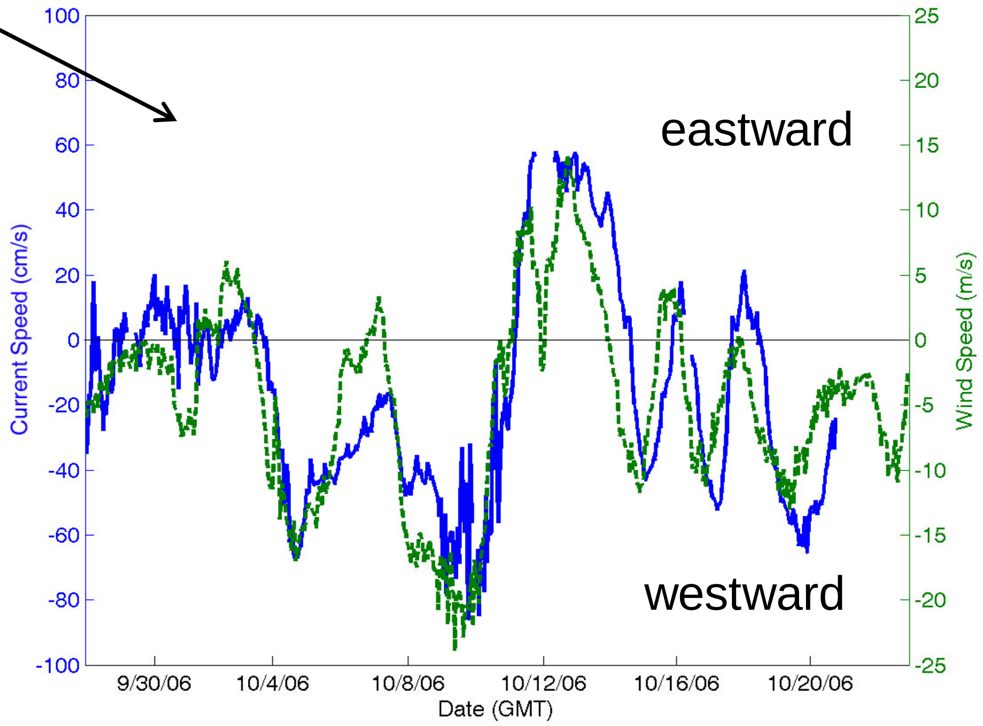
October 2006

Mean winds: 10 m/s westward

Mean Along-shelf Flow: 0.2 m/s (.14 Sv)

Inner shelf volume replaced in 45 days!

From the Mackenzie Shelf!



Impacts winter shelf properties

The Chukchi Shelf

1.) Properties (dynamic and water masses) largely set by Bering Strait.

2.) Bathymetry is key to spatial variability

3.) NE Chukchi Sea (subsurface) waters flow toward Barrow (shelfbreak)

4.) Hanna Shoal region may be a trapping or recirculation zone.

5.) Surface and sub-surface flow may differ (winds and stratification).

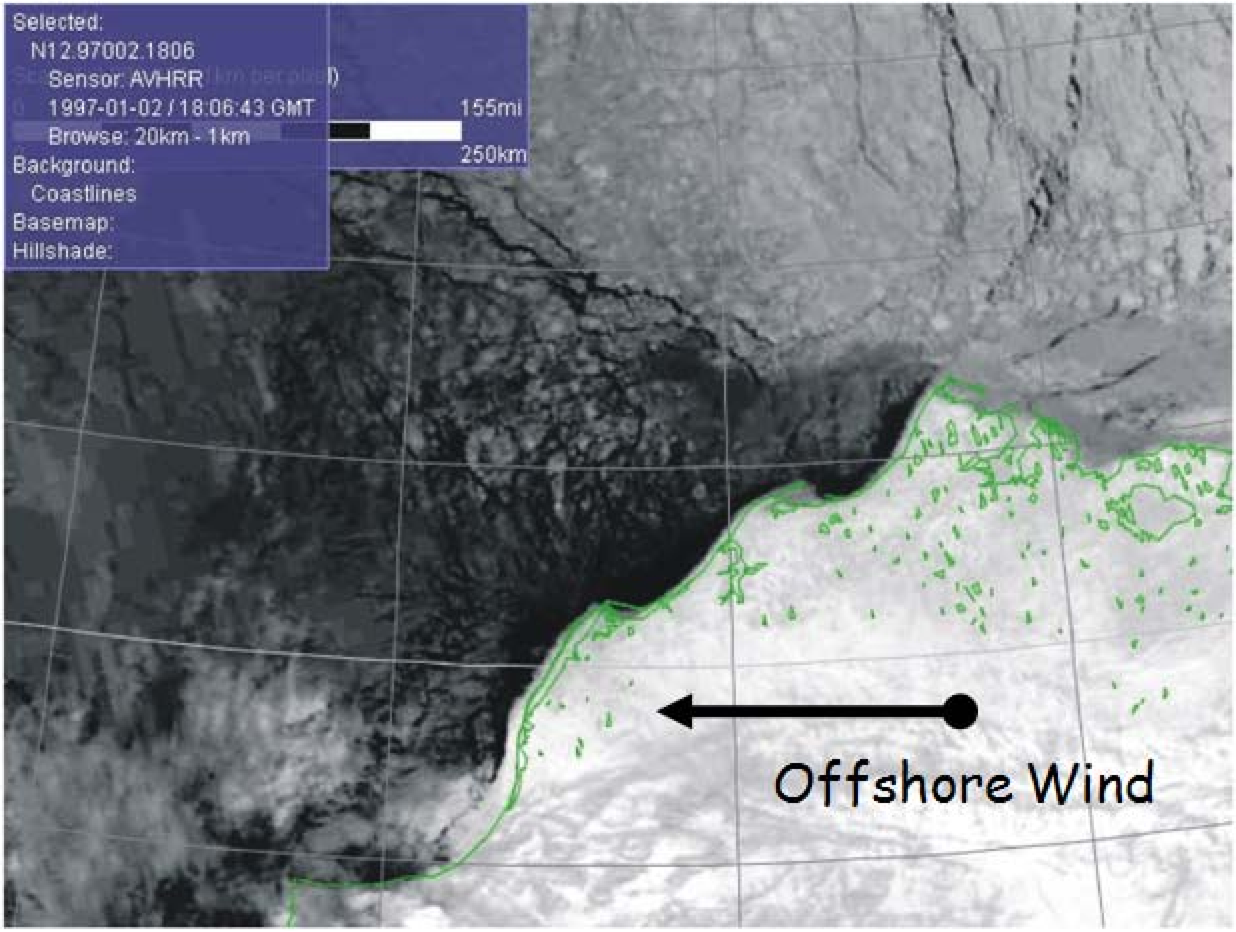
The Alaskan Beaufort Shelf

1. Spatially complex due to boundaries :
   Chukchi, coastal, "oceanic", Mackenzie Shelf and
   pack/landfast ice

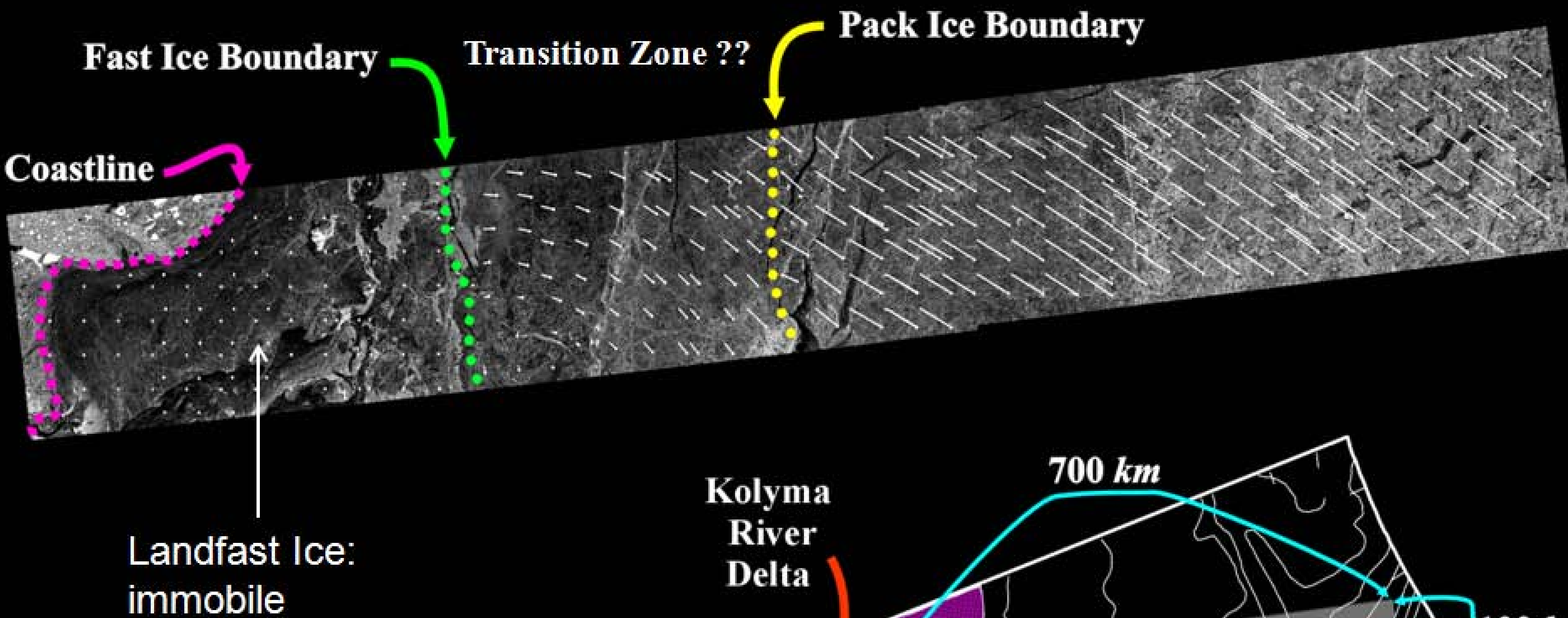
2. Seasonality associated with freeze/thaw cycle;
   seasons change abruptly (within days!)

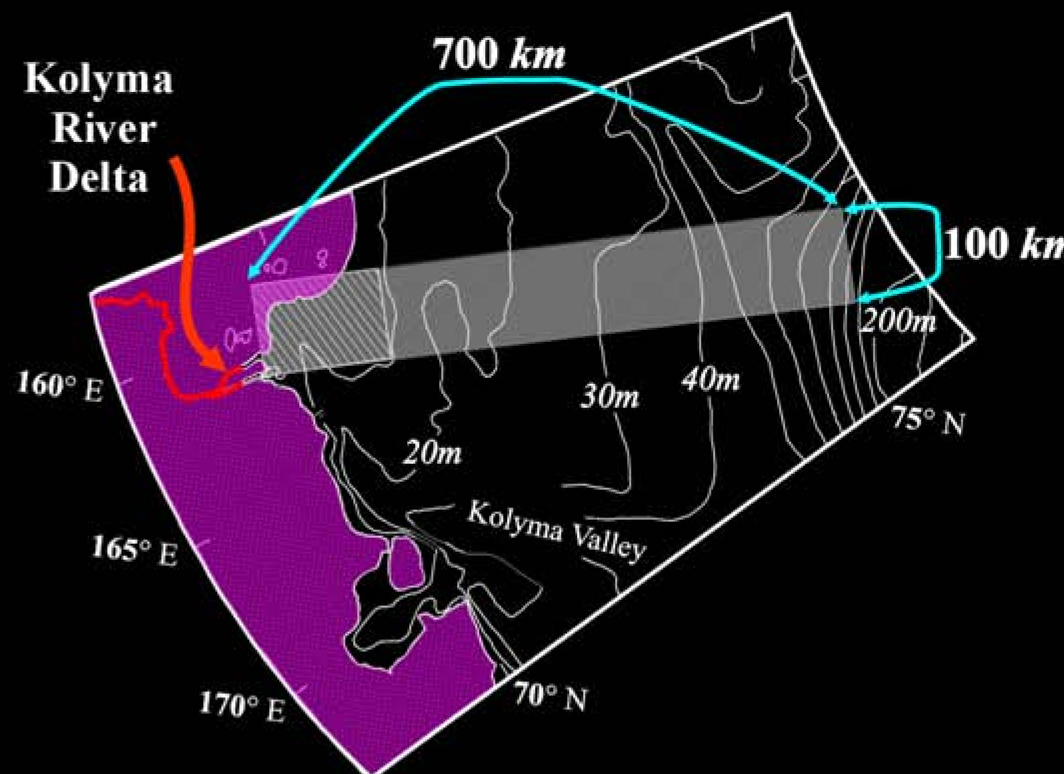
3. Landfast ice:
   dynamics are poorly understood;
   converts large scale wind-forcing into small-scale ocean
   circulation patterns

Chukchi Sea Polynya January 2, 1997



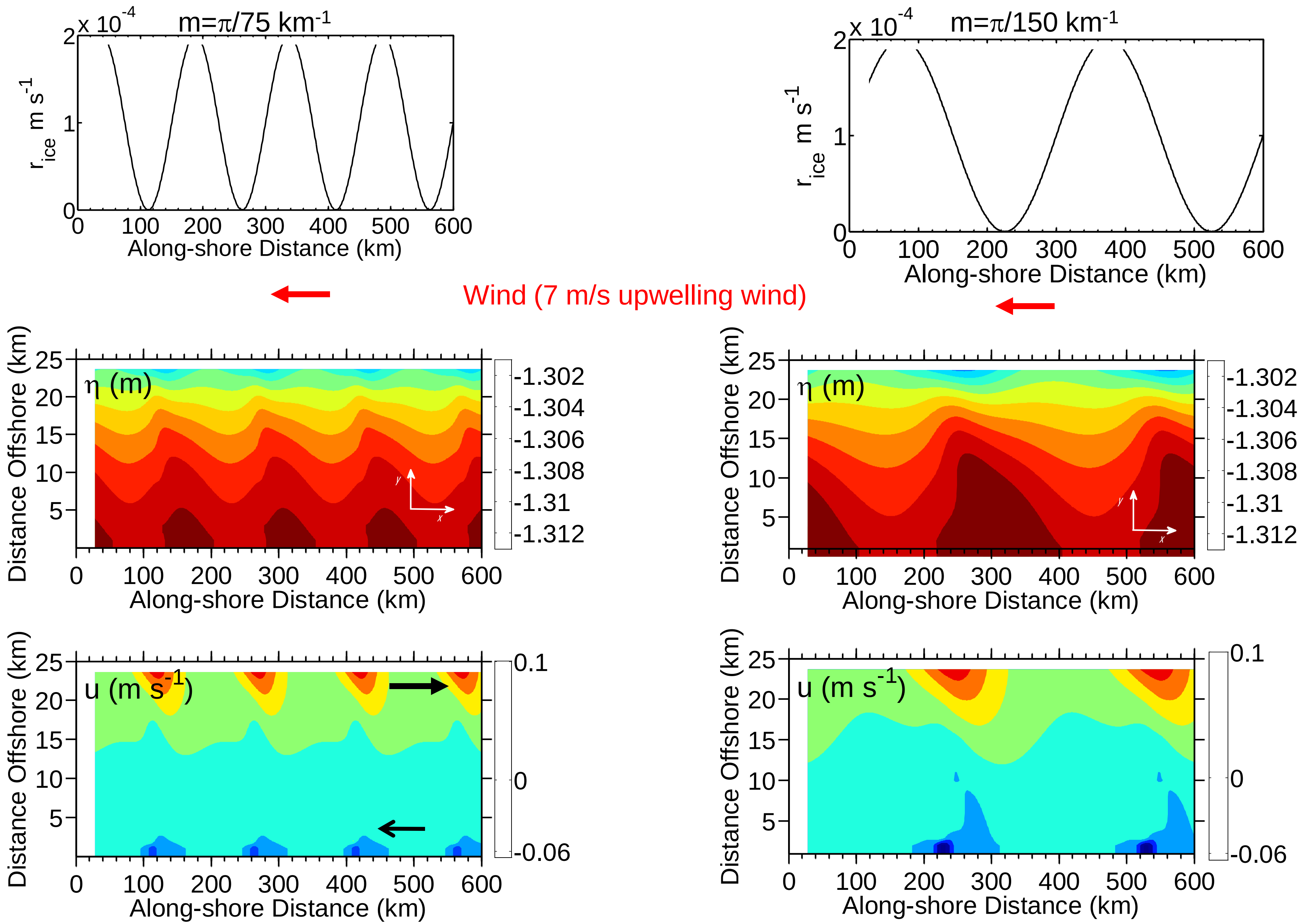
Polynyas:
Cold, saline water formation
Bounded by unstable fronts promote offshore spreading of dense water.
Large interannual variability in occurrence.





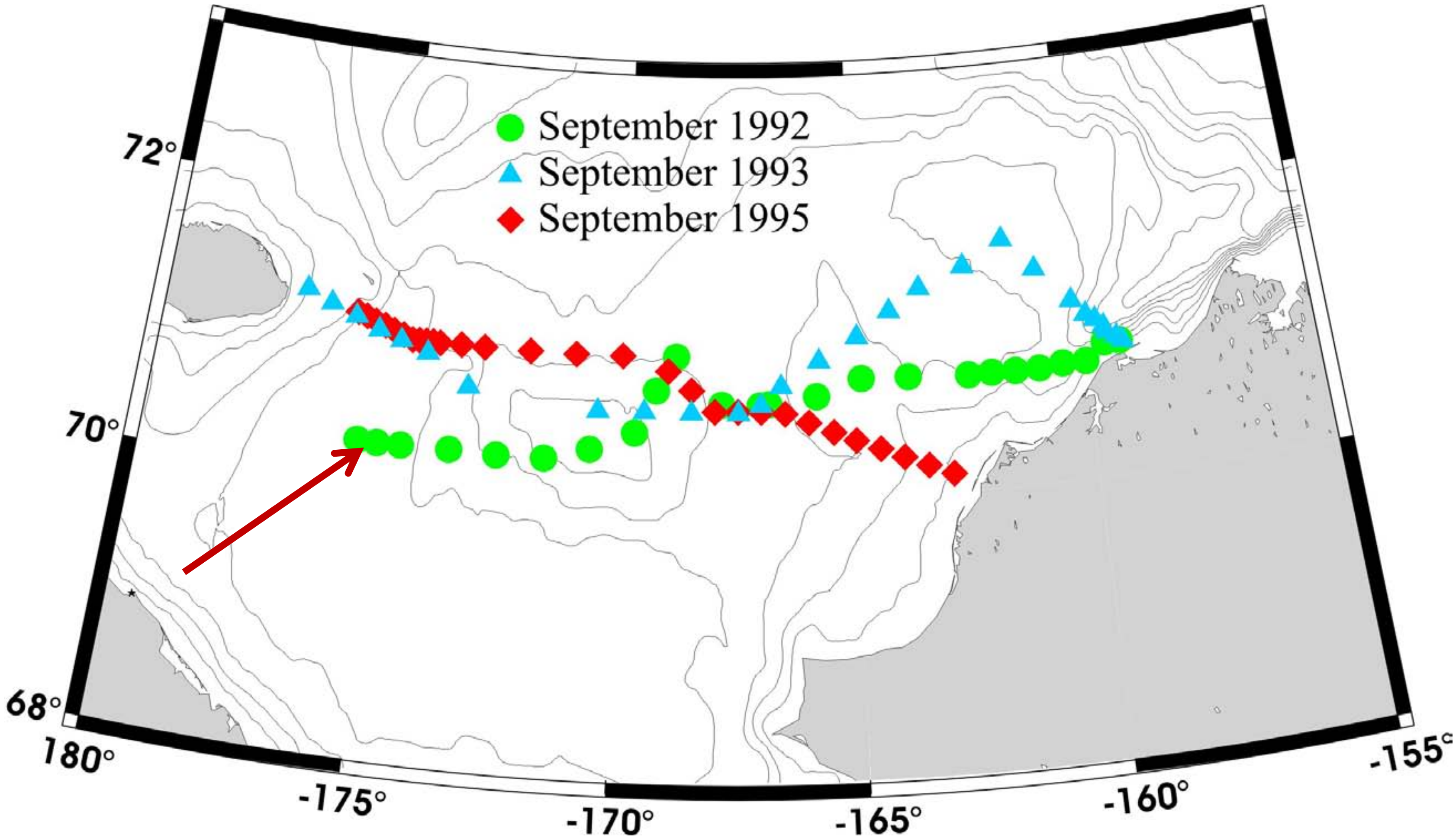
Morris, et. al.
J. of Glaciology,
V.45, No. 150, 1999

Along-shore Variations in r_{ice}

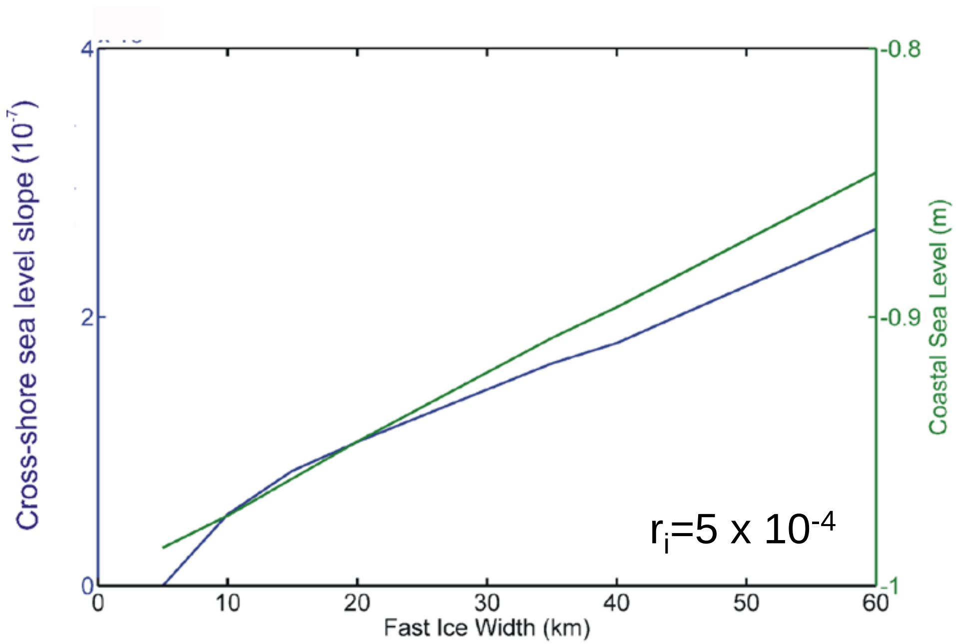


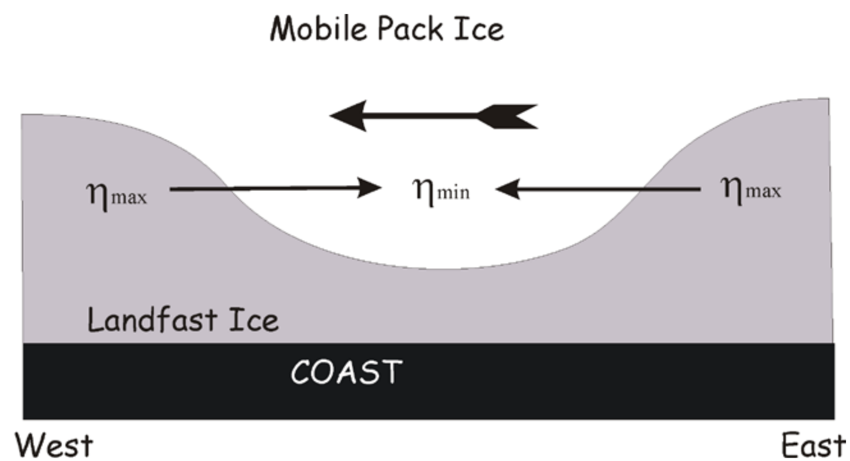
(Kasper and Weingartner, in prep.)

The Bathymetric Influence is reflected in water properties



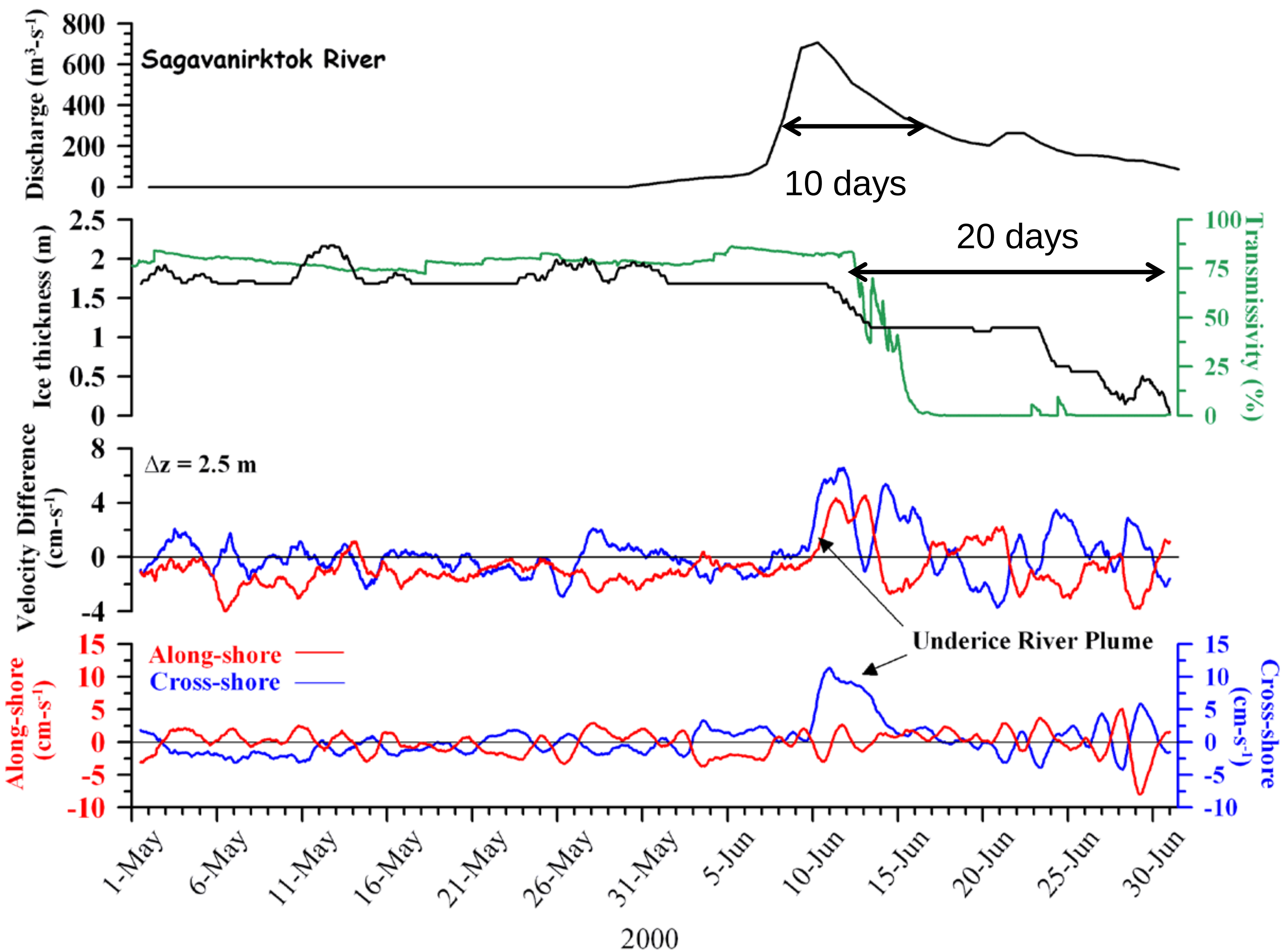
Alongshore variations in ice width (and/or "transition zone") leads to along-shore pressure gradients.



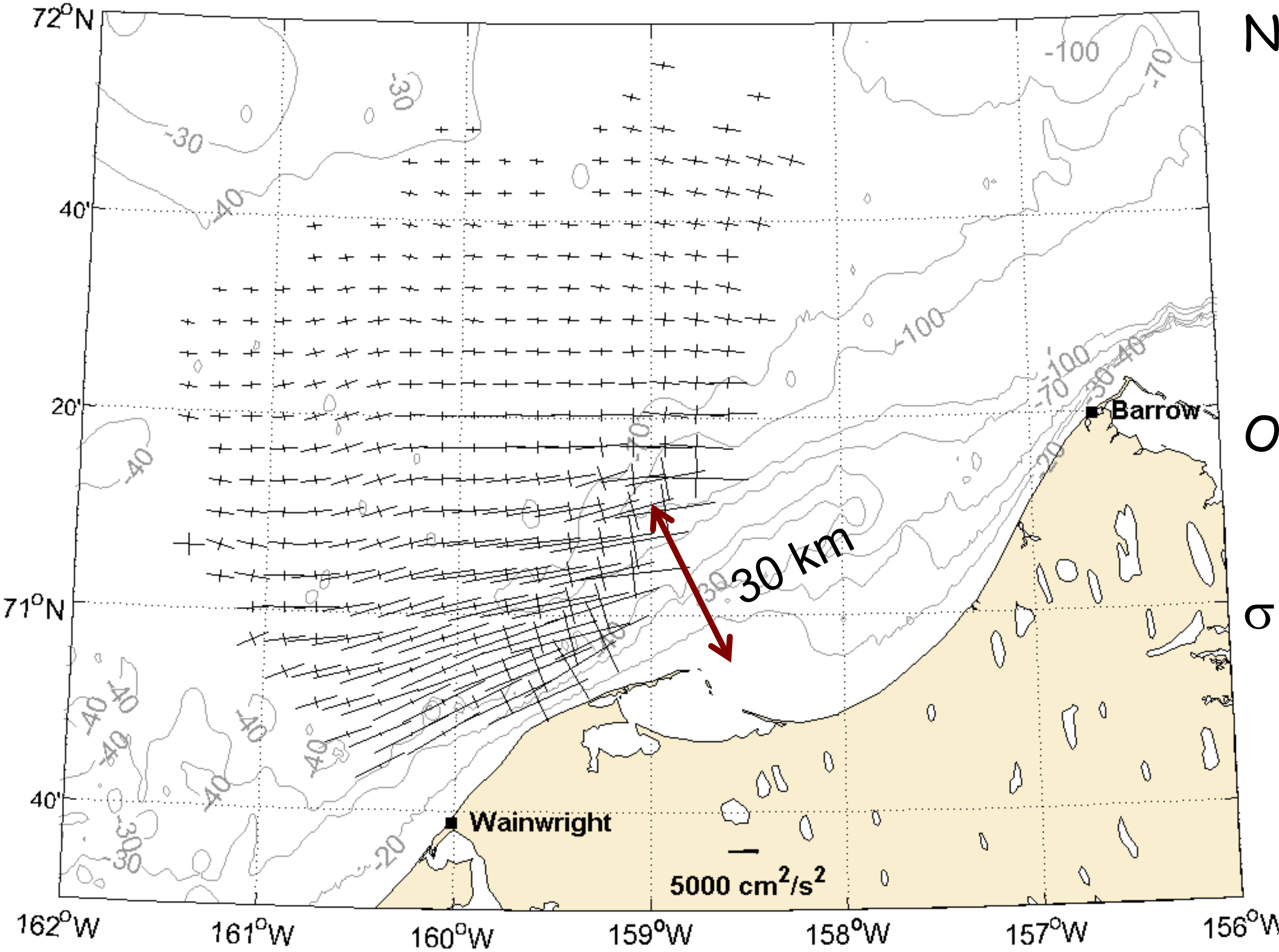


Ice-ocean friction and ice width are set by landfast ice dynamics: reduces along-shore correlation scale of the currents

May-June: runoff, ice thickness, transmissivity, velocity shears, and current speeds



Sept – Oct. 2009 Principal Axes of Variance



NEARSHORE (~30 km)
oriented along-shore
Width consistent with
stratified coastal
ocean dynamics.

OFFSHORE:
east-west orientation

$\sigma^2_{nearshore} \sim 10\, \sigma^2_{offshore}$

Cooperative Institute for Research in Environmental Sciences

National Snow and Ice Data Center
Supporting Cryospheric Research Since 1976

University of Colorado

Arctic Sea Ice Observations

Walt Meier

BOEMRE Workshop
McLean, VA, March 29, 2011

http://nsidc.org

National Snow and Ice Data Center

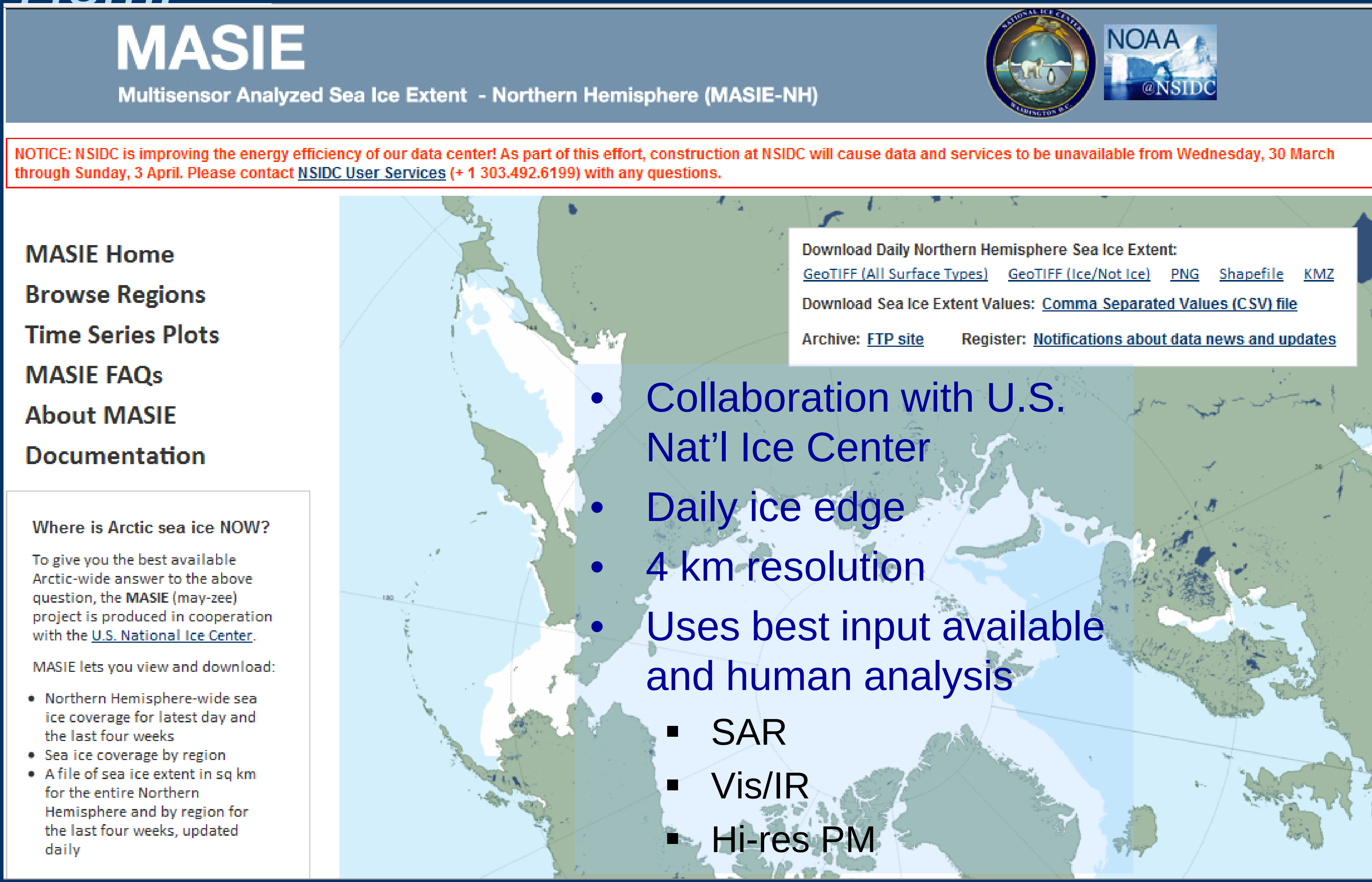
- Part of CIRES, cooperative institute between NOAA and Univ. Colorado
- NASA Distributed Active Archive Center (DAAC)
  - Archive and distribute NASA EOS cryosphere products and other NASA data
- Archive NOAA, NSF and other cryosphere data as well
- Most funding (~75%) from NASA
- ~12 research scientists

Photo credit: Ted Scambos

Sea ice extent, concentration observations

- *Pre-1953*: regional observations only
- *1953 – 1972*: operational ice charts
- *1972 – 1977*: ice charts and early satellite
- *Nov 1978 – present*: multi-channel passive microwave
  - Consistent, complete, daily observations of entire Arctic Ocean and surrounding seas
    - NOAA Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), Nov 1978 – Aug 1987
    - Defense Meteorological Satellite Program Special Sensor Microwave Imager (SSM/I), Jul 1987 – present

Multi-sensor Analyzed Sea Ice Extent – N. Hem.

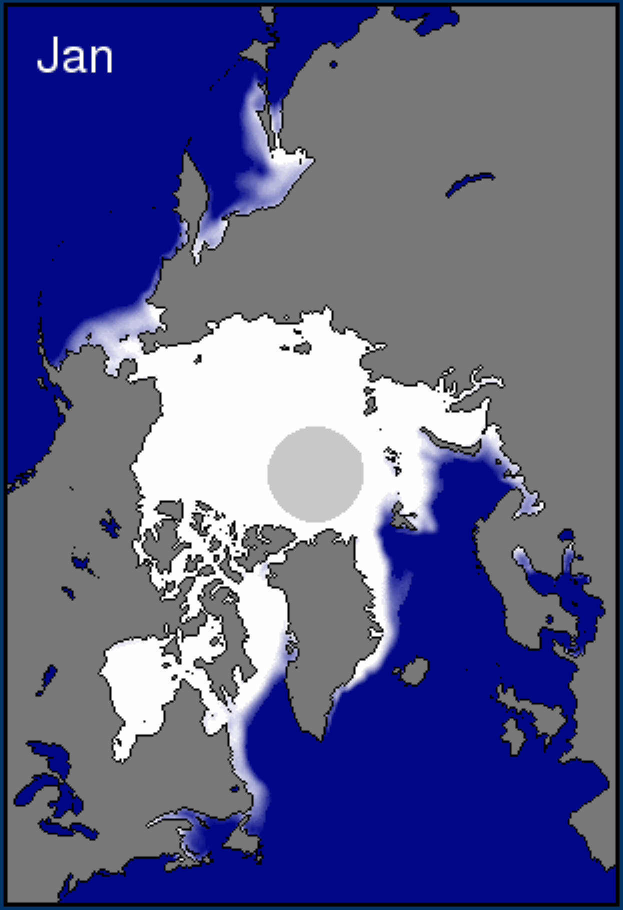


- Collaboration with U.S. Nat'l Ice Center
- Daily ice edge
- 4 km resolution
- Uses best input available and human analysis
  - SAR
  - Vis/IR
  - Hi-res PM

http://nsidc.org/data/masie/

Passive microwave sensors for sea ice

- Complete daily coverage
- Little effect from clouds
- Independent of solar radiation
- Low spatial resolution (~25-50 km)
  - Radar, vis/IR provide higher resolution, but over limited regions on any given day and some records (radar) cover limited timespan

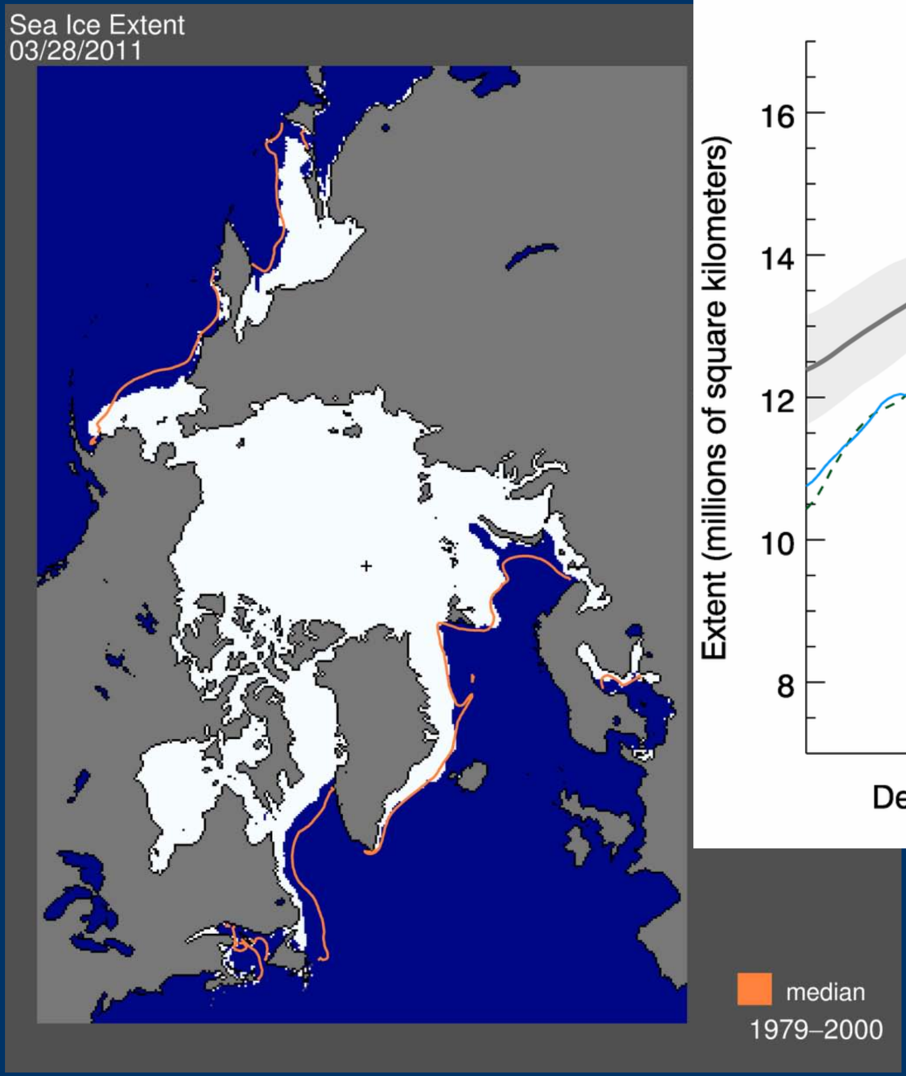


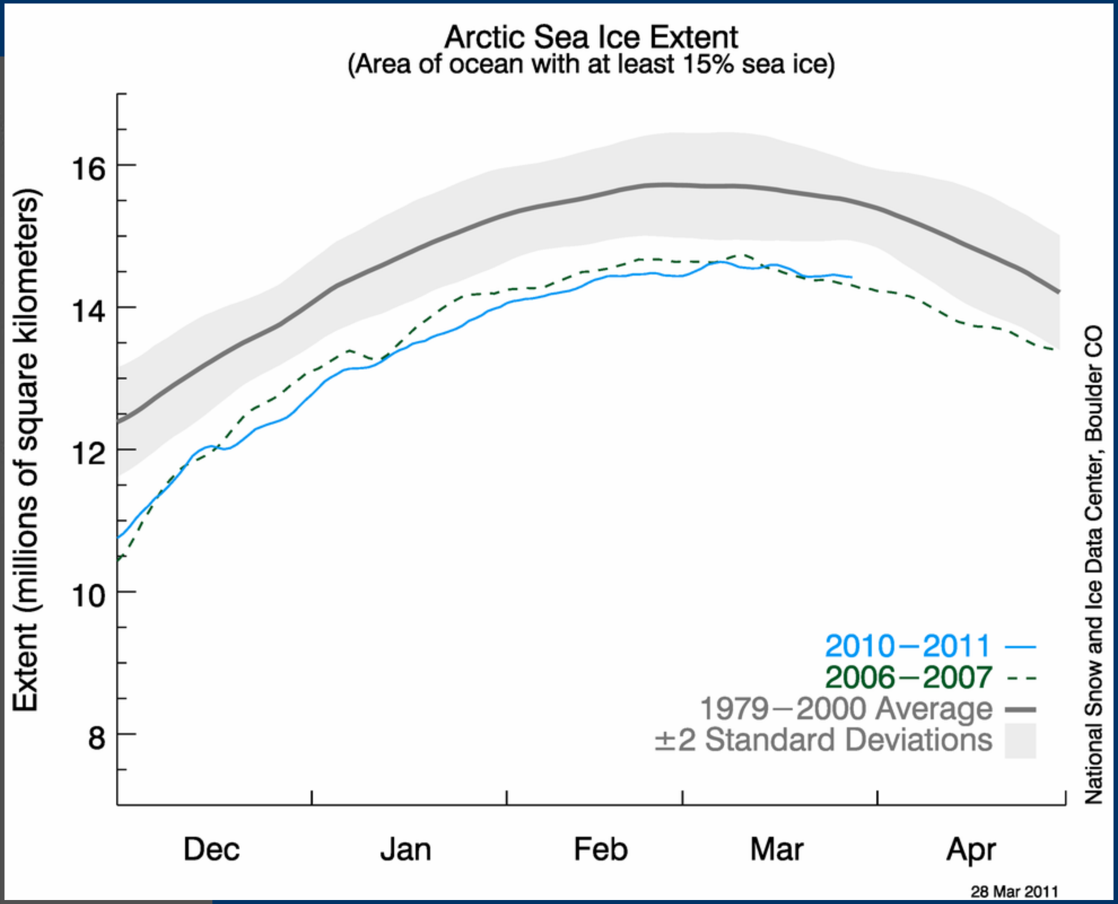
1979-2000 Monthly Average Concentration

Passive microwave sea ice algorithms

- Several algorithms (three developed at NASA Goddard)
  - Generally products are offset from each other – i.e., absolute numbers vary, but trends and anomalies are fairly consistent between them
  - Regional and seasonal differences occur
  - Different products should not be combined
- This presentation: NASA Team algorithm distributed at NSIDC

Passive microwave daily sea ice estimates

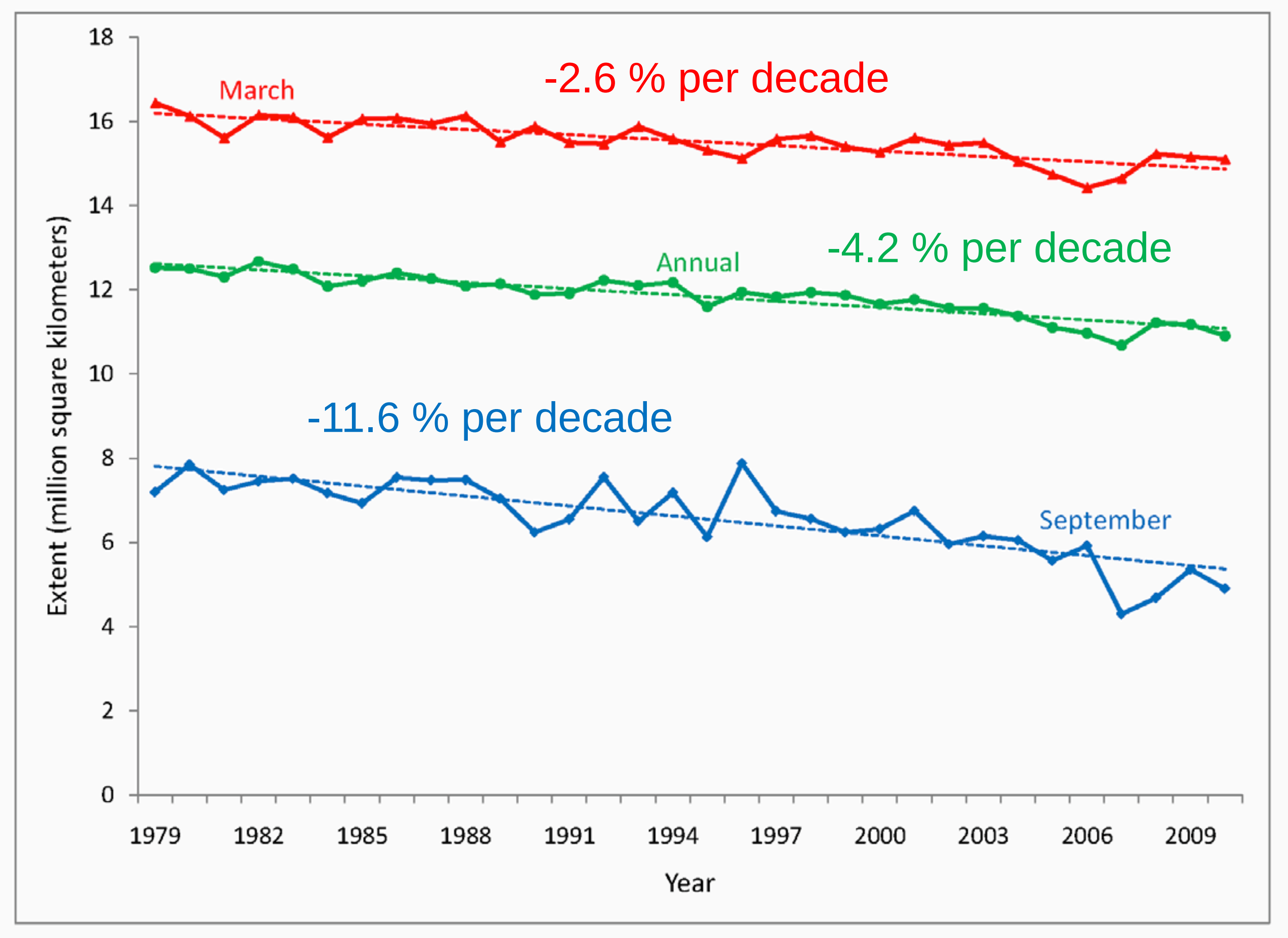




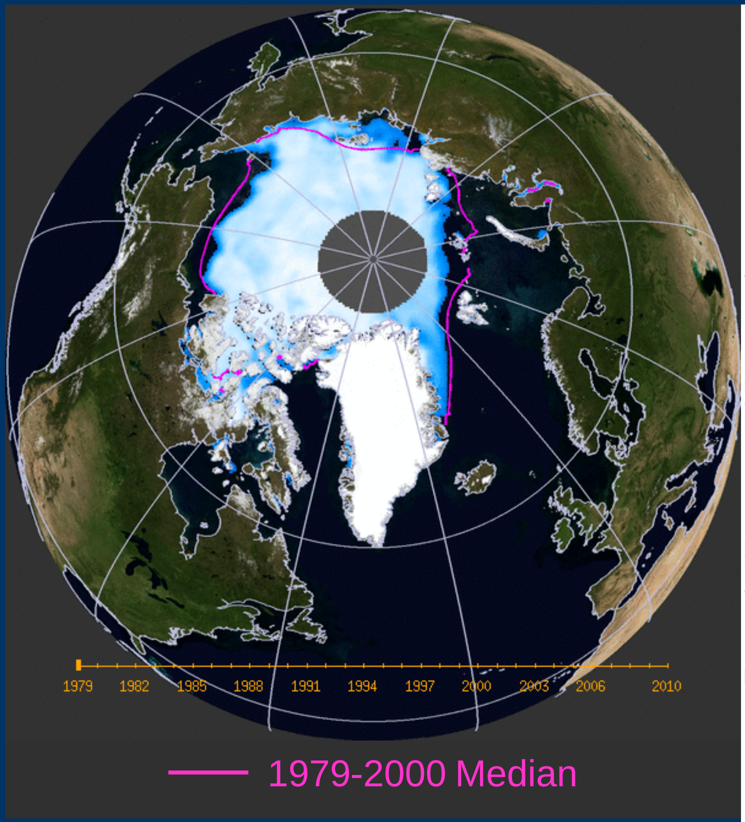
NSIDC Arctic Sea Ice News and Analysis

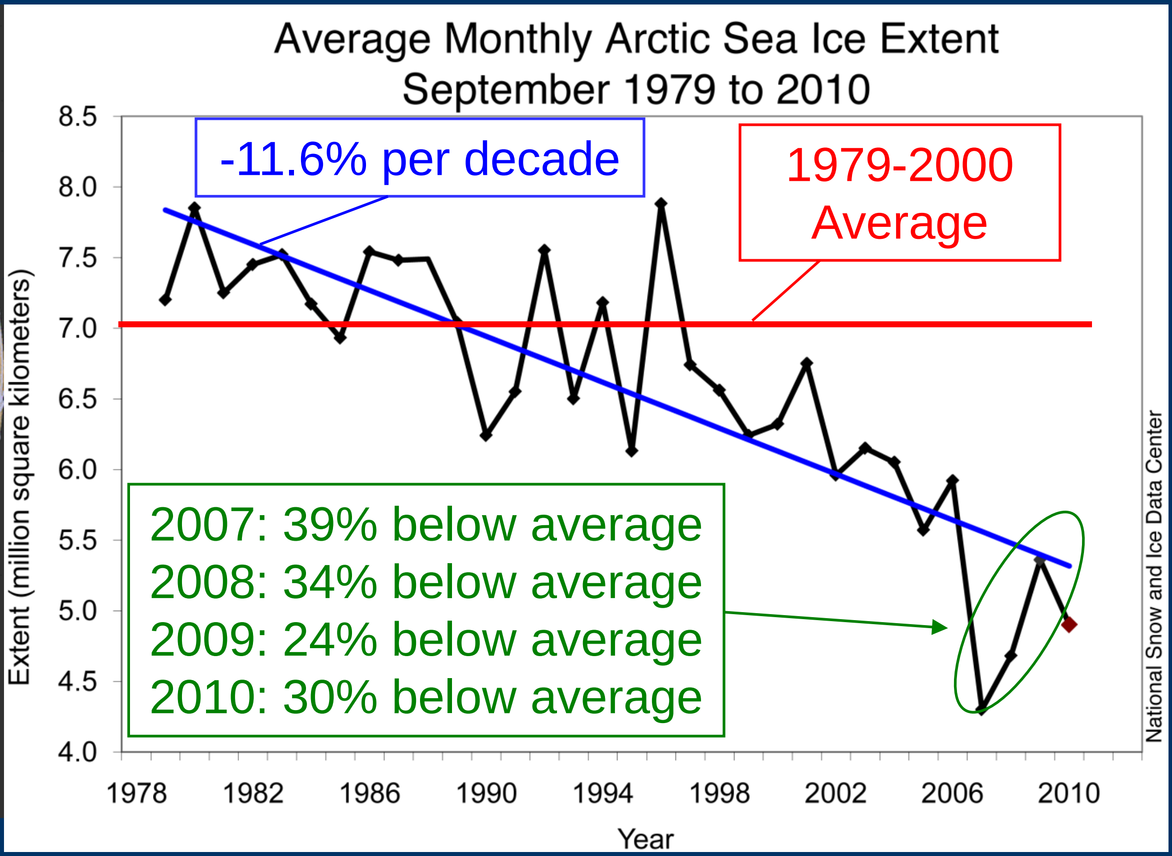
http://nsidc.org/arcticseaicenews/

Winter, summer, annual sea ice extent

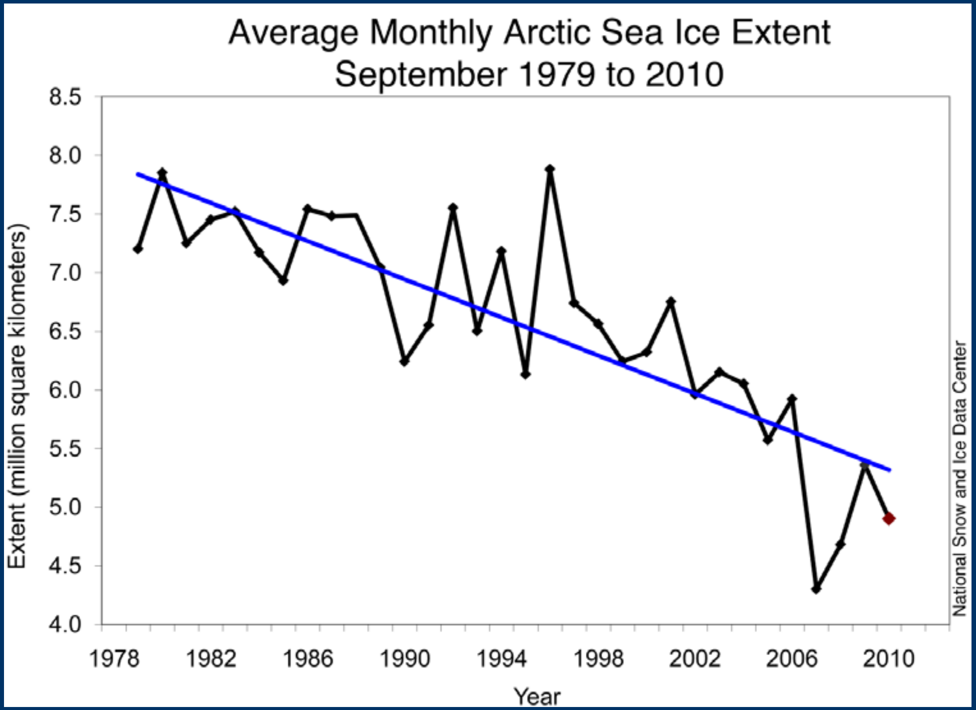


Summer Arctic sea ice is declining



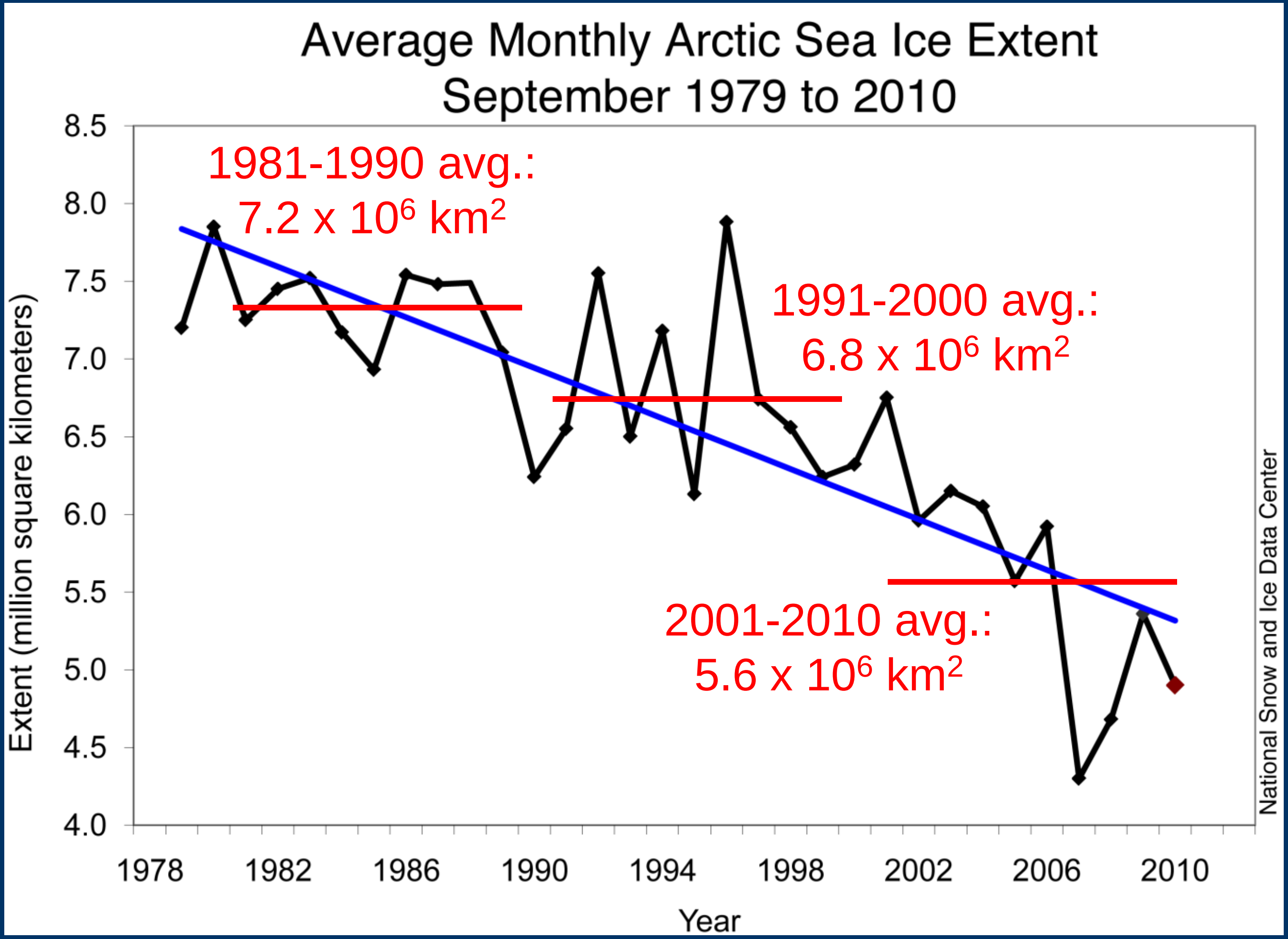


Accelerating September trend

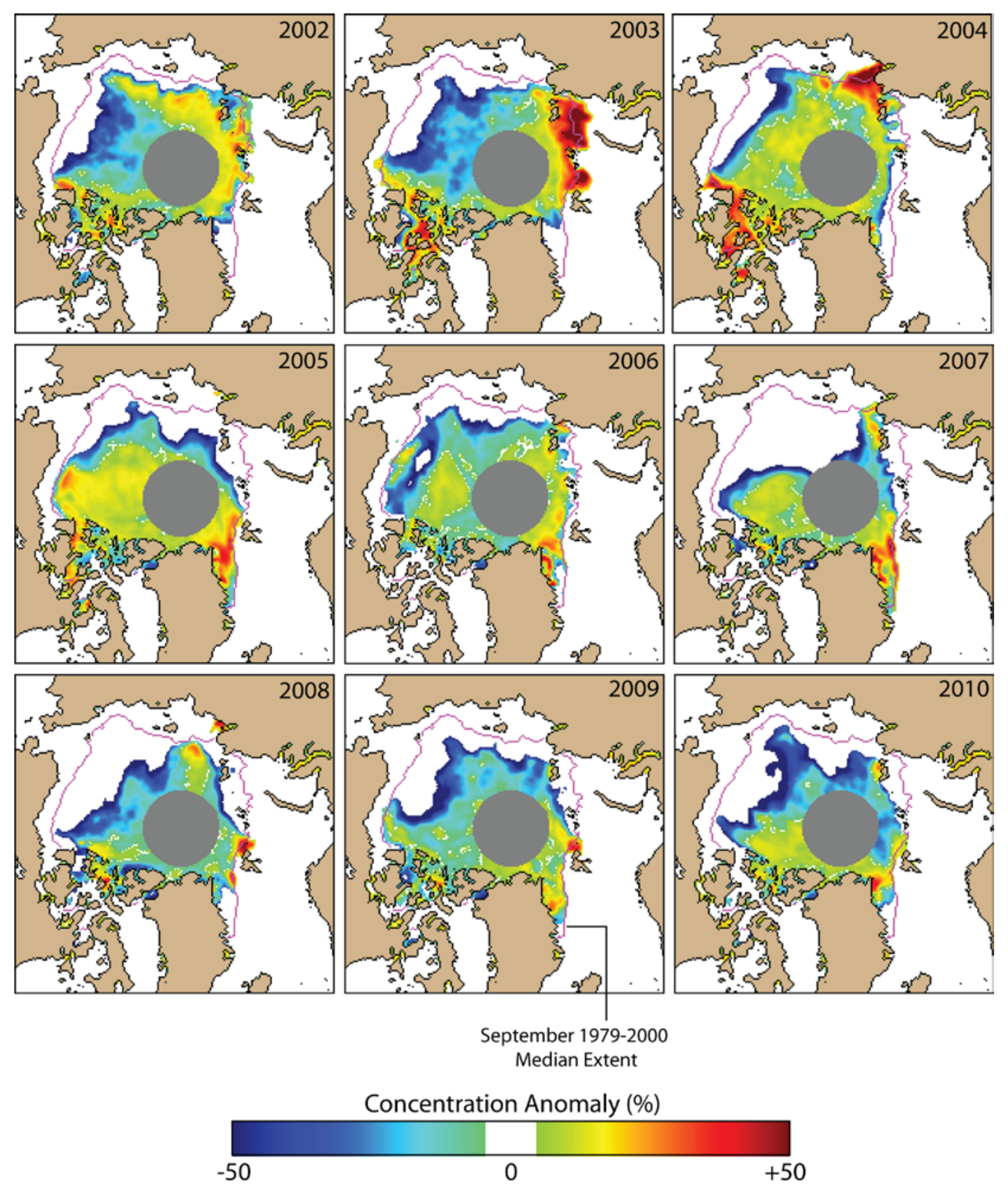


Years	Trend (km^2/yr)	%/decade relative to 79-00 avg.
79-01	-45900	-6.5
79-02	-51000	-7.3
79-03	-52800	-7.5
79-04	-54600	-7.8
79-05	-59400	-8.4
79-06	-60200	-8.6
79-07	-71600	-10.2
79-08	-78100	-11.1
79-09	-78700	-11.2
79-10	-81400	-11.6

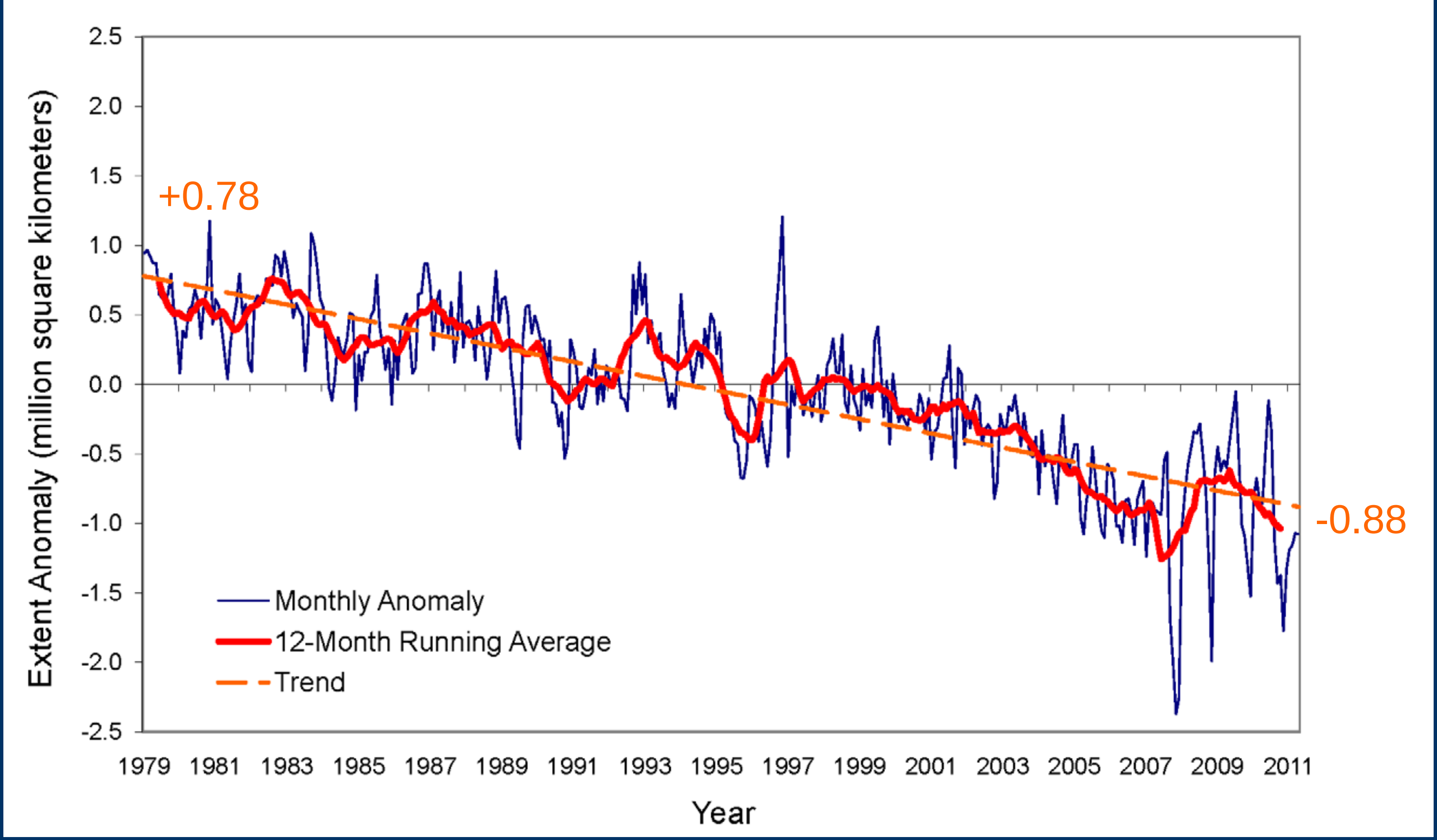
Accelerating September trend



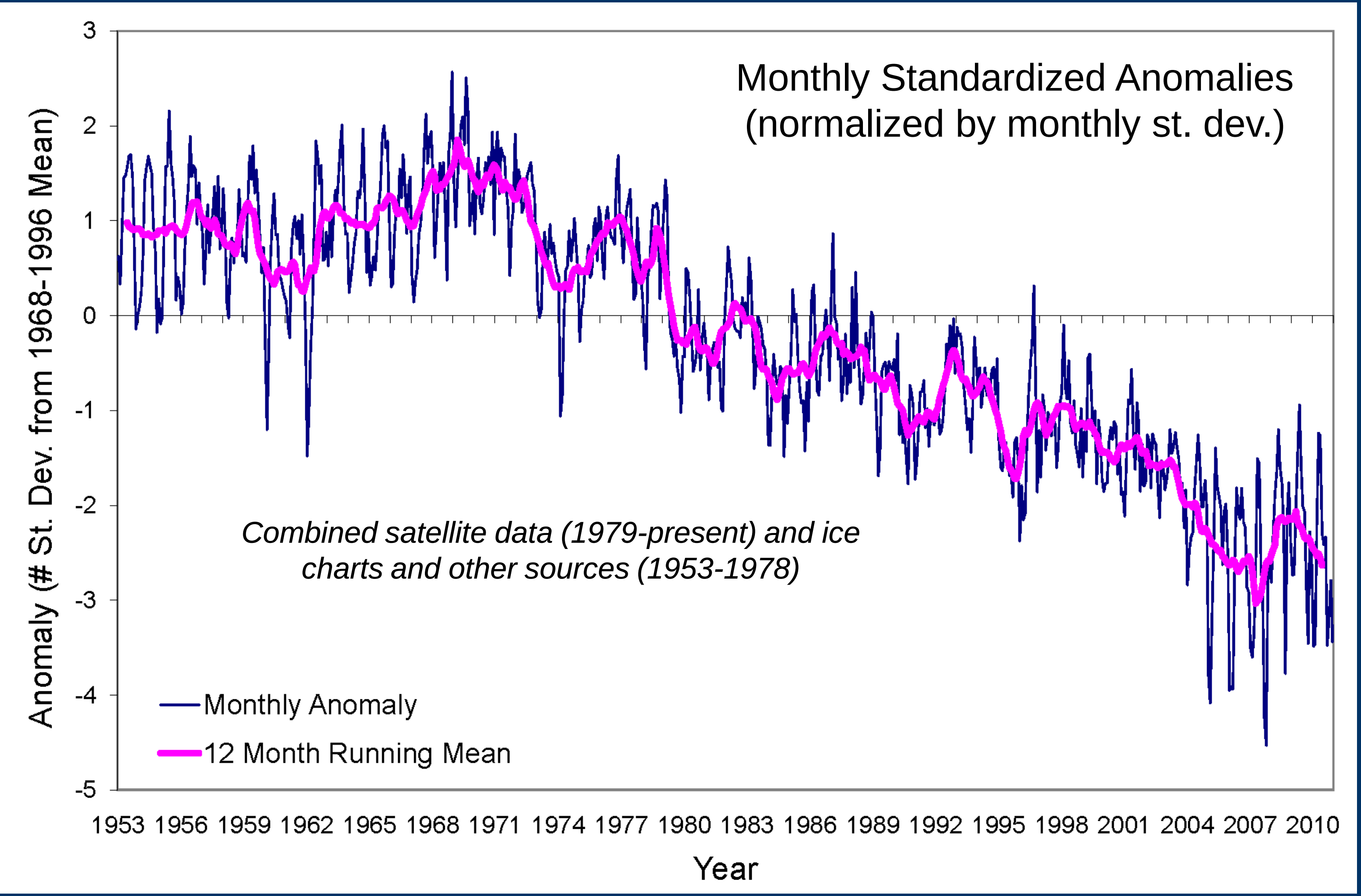
September Concentration Anomalies, 2002-2010



Satellite era anomaly trend, Nov 1978 – Feb 2011

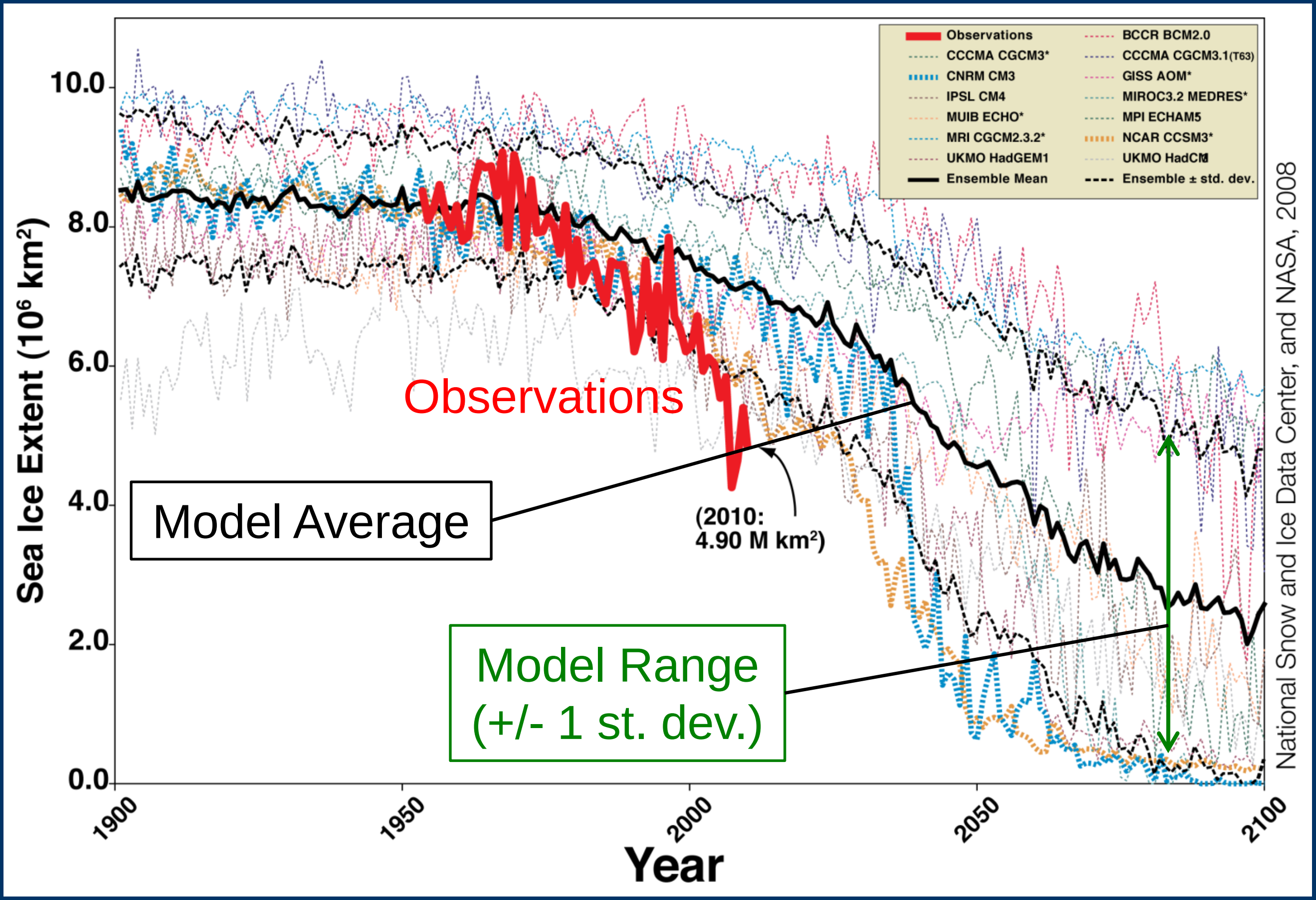


Pre-satellite and satellite, Jan 1953 – Dec 2010



From Hadley Centre UK ISST dataset, with adjustments for consistency

Observations faster than forecast by IPCC models



Arctic September Average Sea Ice Extent

IPCC AR4 models,1900-2100

Observations, 1953-2010

Updated from Stroeve et al., 2007

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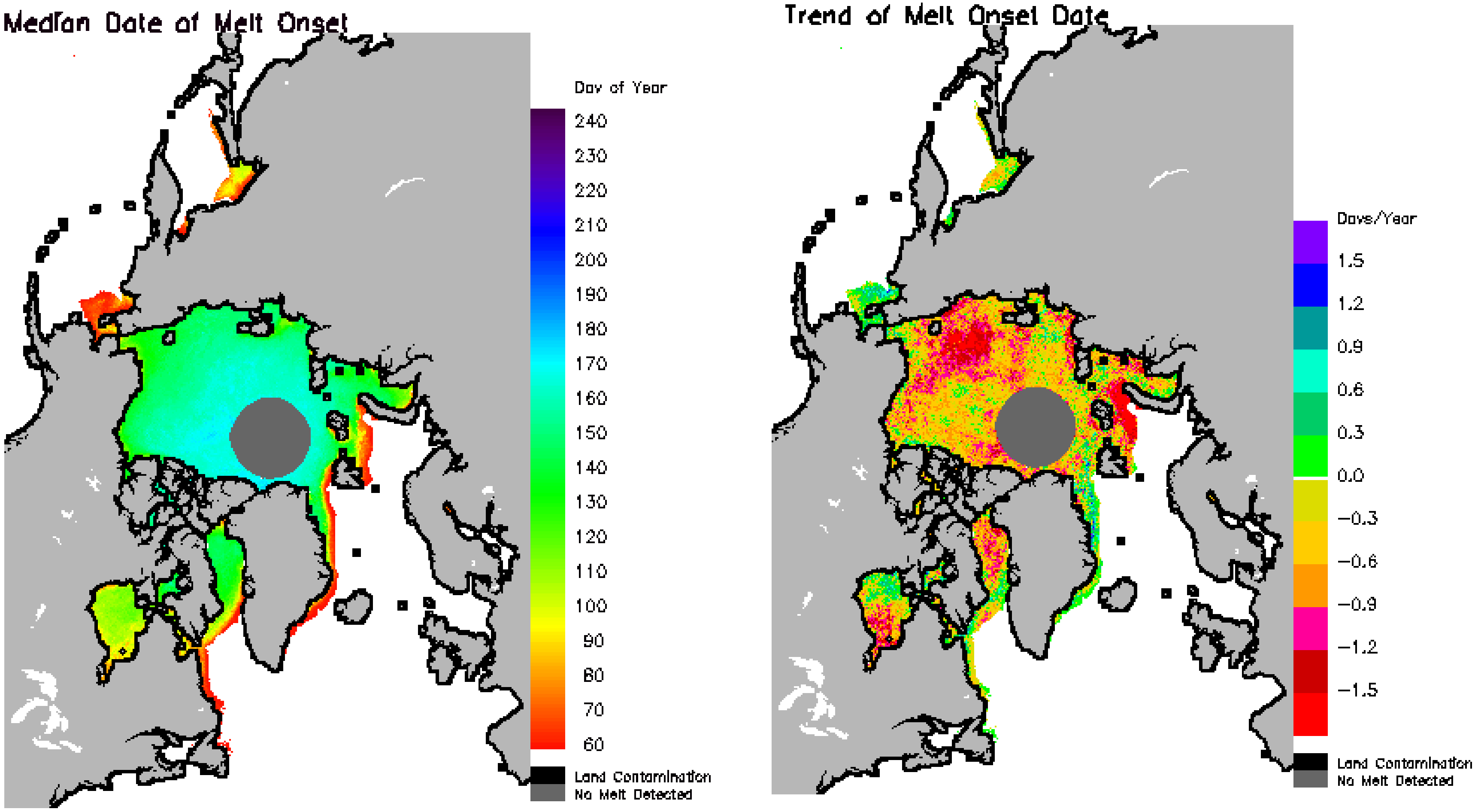
Snow melt onset on sea ice

1979-2007



From passive microwave data
Drobot and Anderson, 2001: http://nsidc.org/nsidc-0105.html

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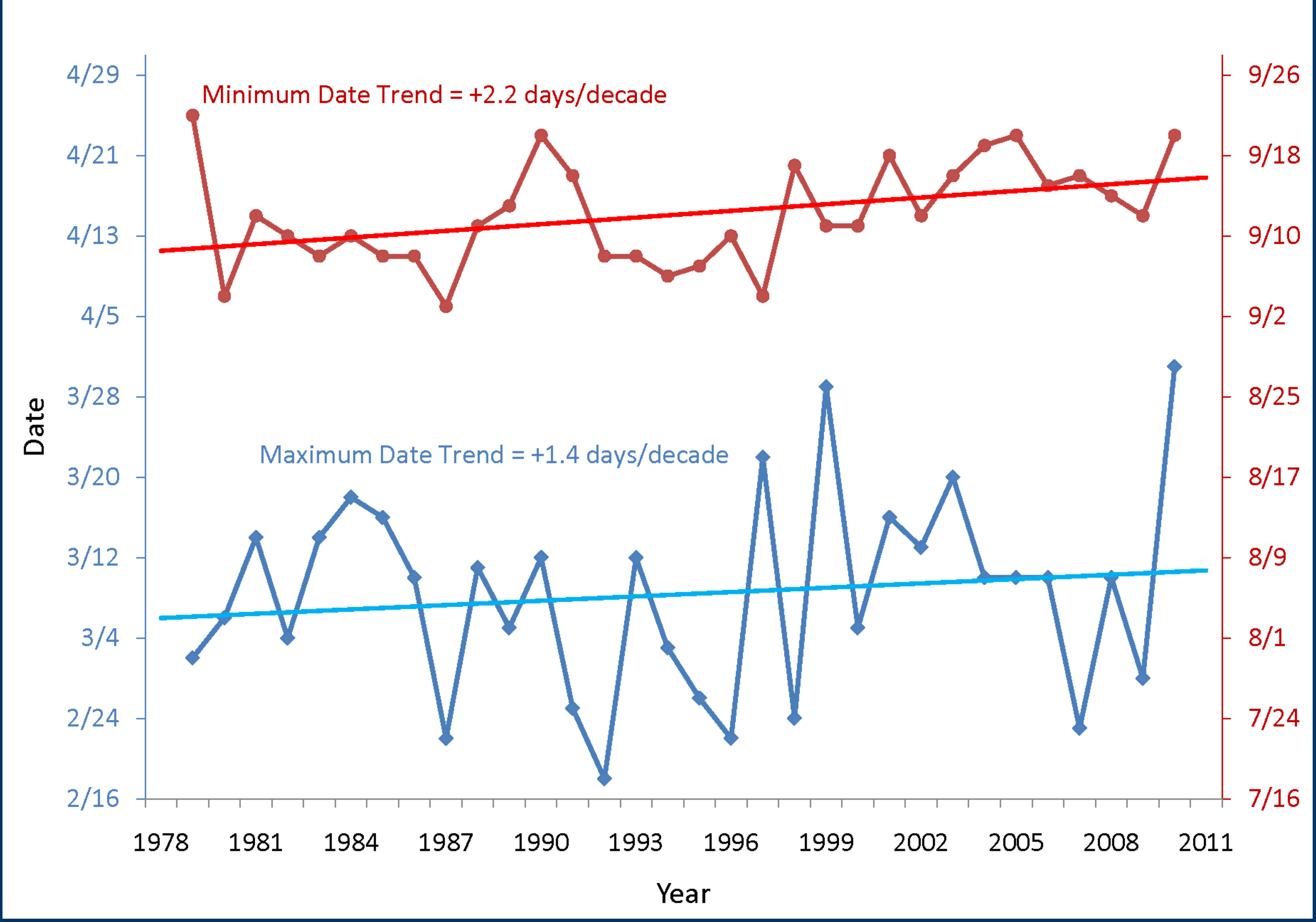
“Summer” season shifting, lengthening



Sea ice age

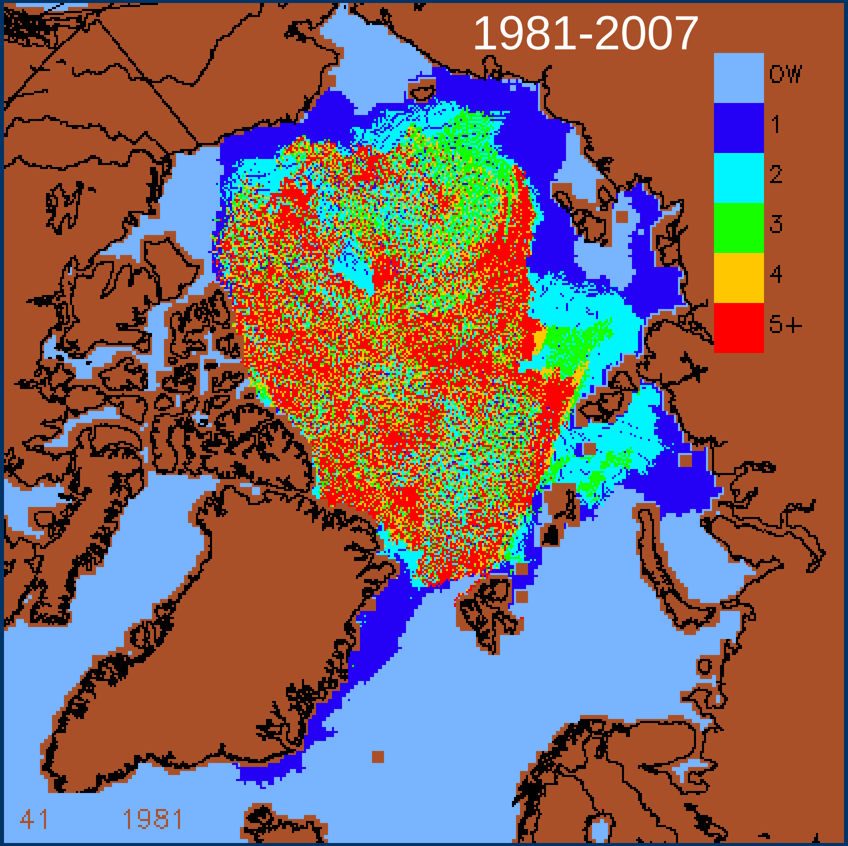
- Proxy for ice thickness
  - Other things being equal:

Older ice = Thicker ice

- Developed by J. Maslanik and C. Fowler, University of Colorado
- Lagrangian tracking of ice parcels
- Passive microwave data, visible imagery, buoys – 1979-present

Ice is getting younger and thinner

Sea ice moves with winds and currents.
Moves out of Arctic along Greenland coast, replenished by new ice.



Based on satellite observations; from J. Maslanik, C. Fowler, Univ. Colorado

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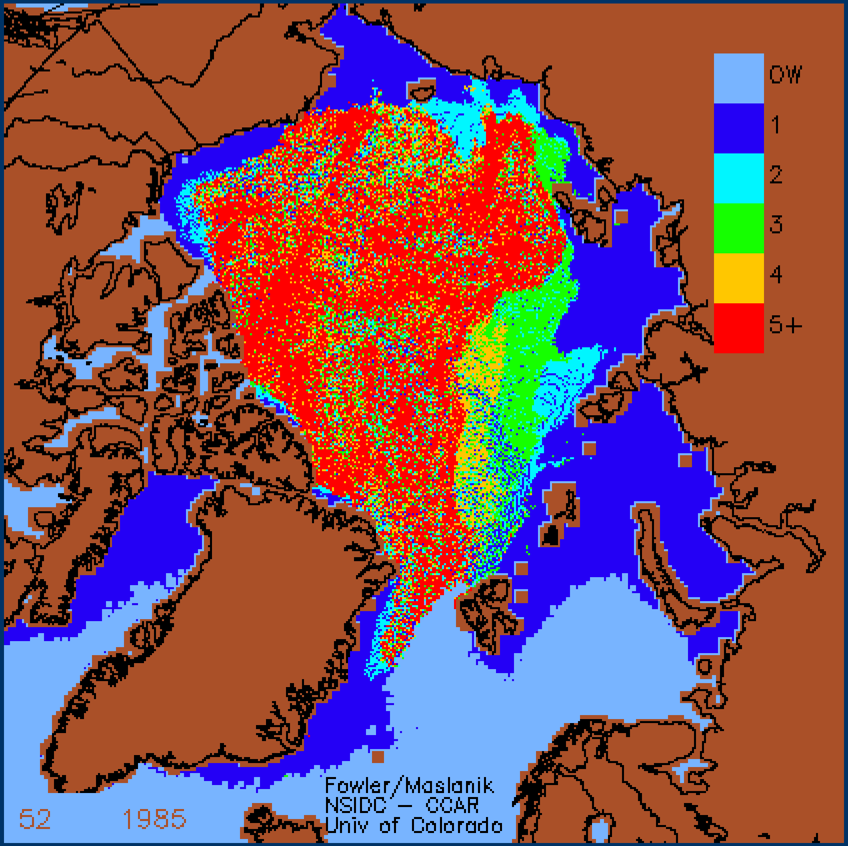
Ice is getting younger and thinner

Old, ice used to covered most of central Arctic.
Now it is mostly limited to a narrow band along Greenland and Canadian Archipelago.

End December 1985-2010

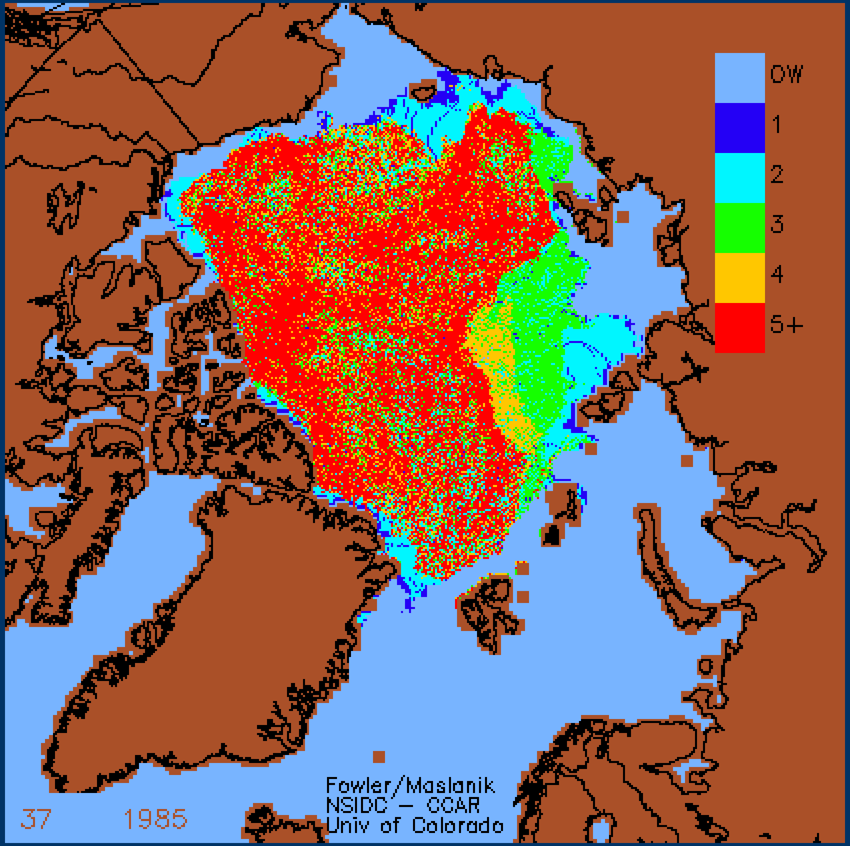


Based on satellite observations; from J. Maslanik, C. Fowler, Univ. Colorado

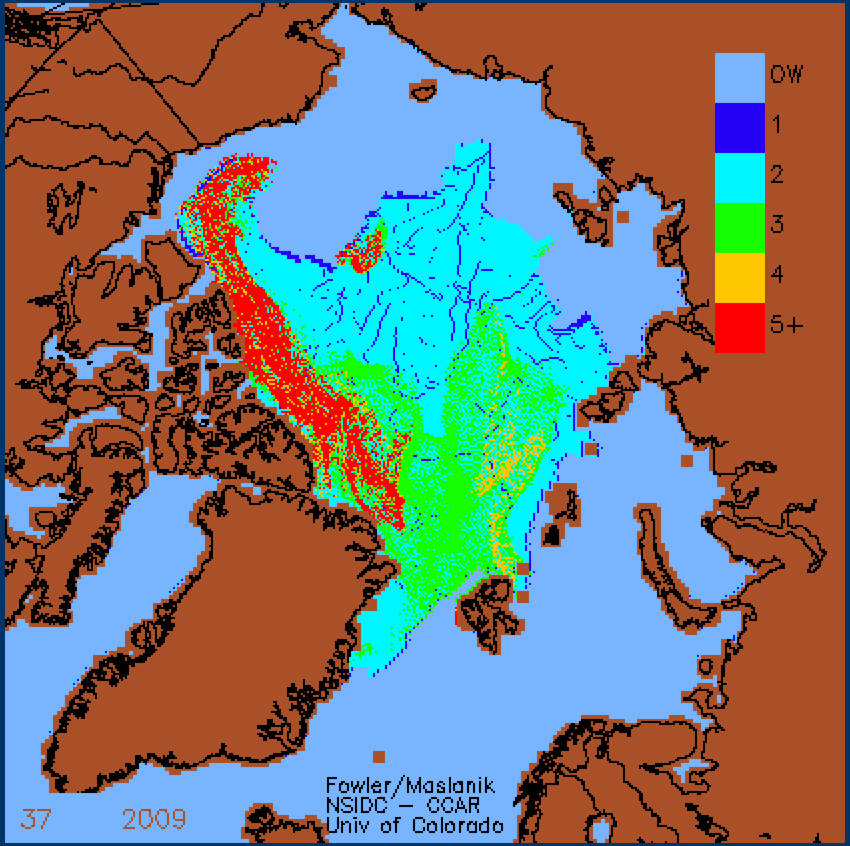
Ice is getting younger and thinner

Much of older, thicker ice north of Alaska melting away during summer

Sep 1985 – Dec 1986

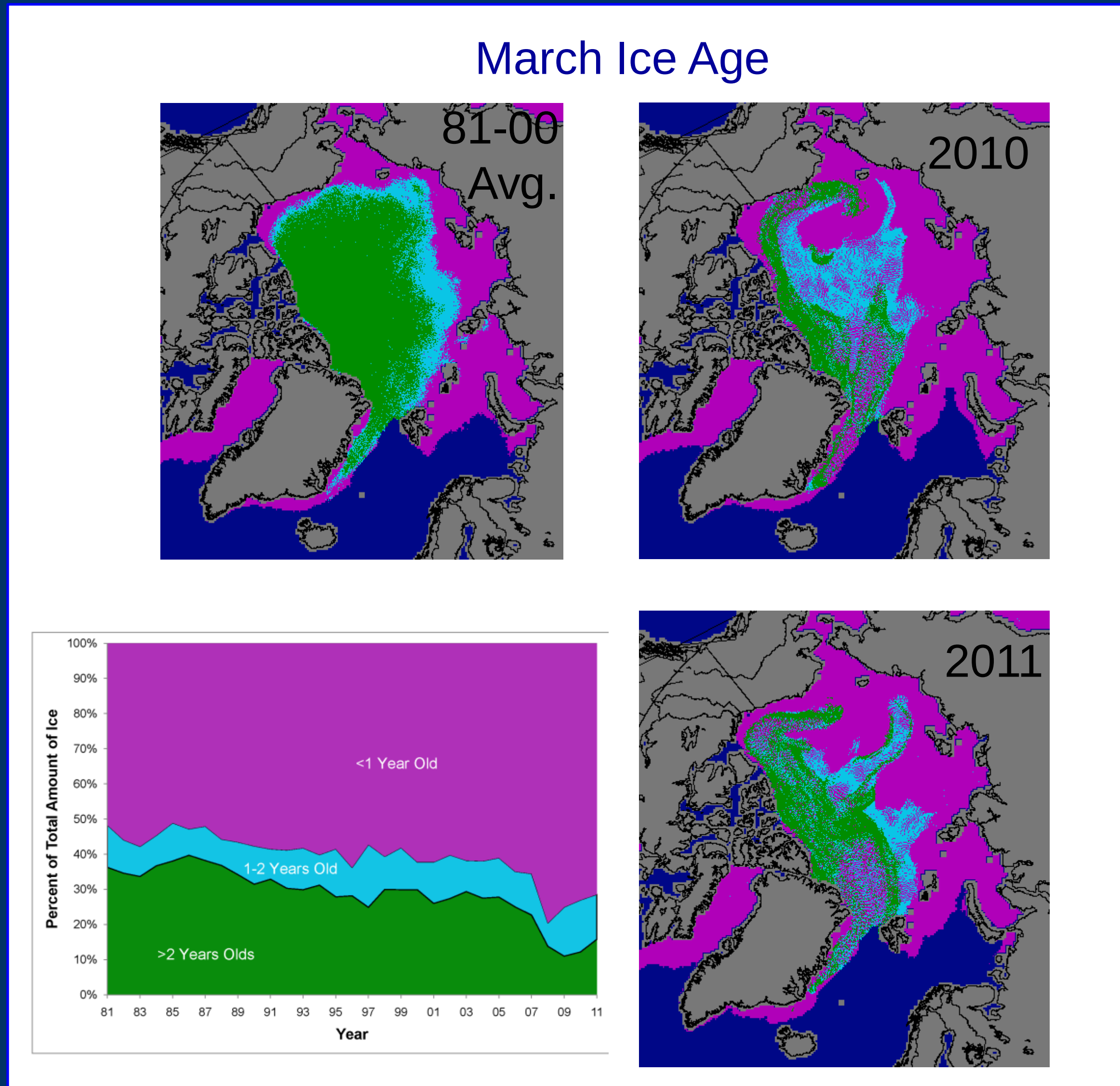


Sep 2009 – Dec 2010



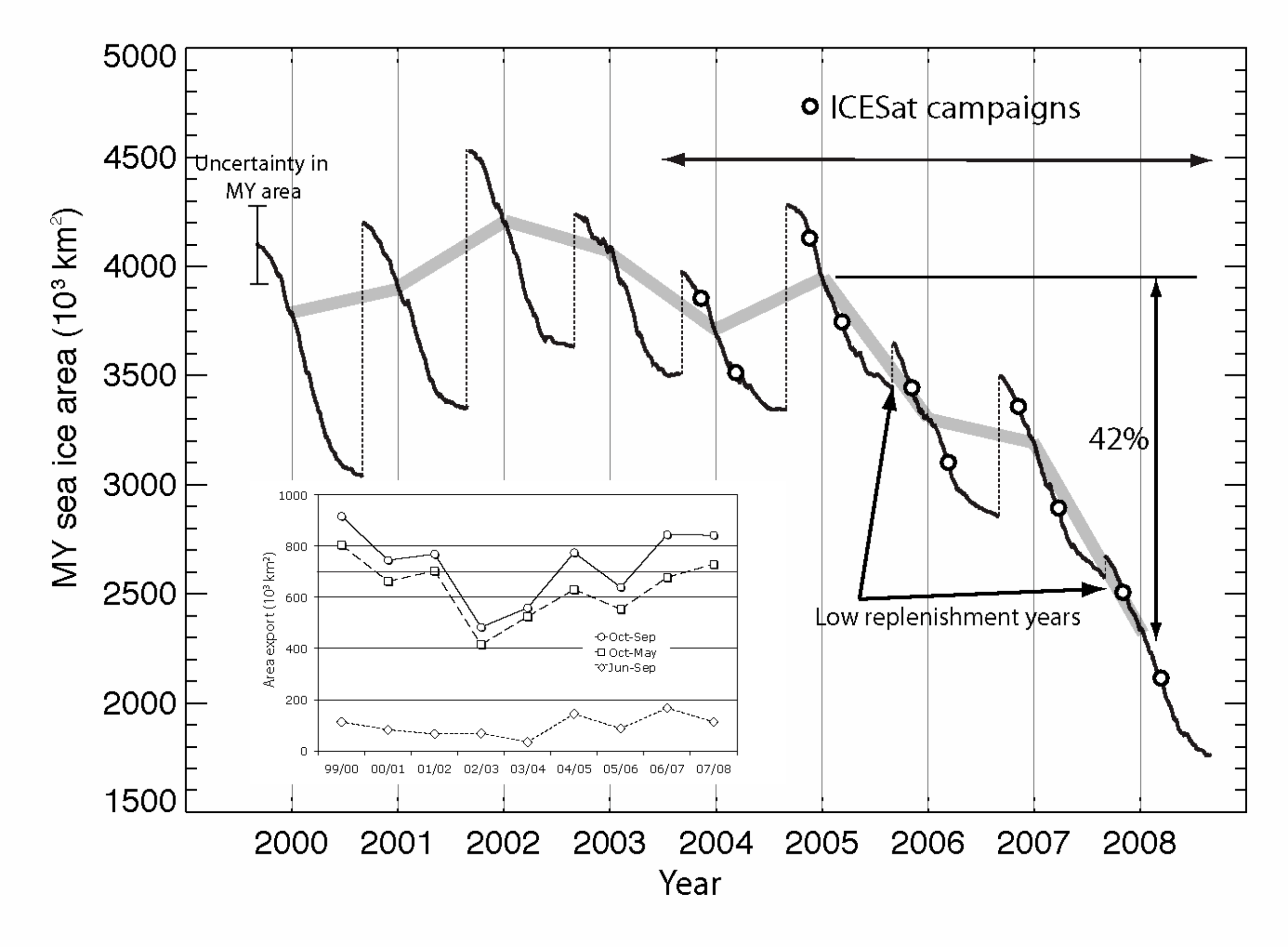
Based on satellite observations; from J. Maslanik, C. Fowler, Univ. Colorado

Sea ice age, a proxy for ice thickness



Based on satellite observations; from J. Maslanik, C. Fowler, Univ. Colorado

Multiyear ice from scatterometer data



Changes in Sea Ice Motion

Area flux through a gate:

Beaufort Sea, 1997 vs. 2008

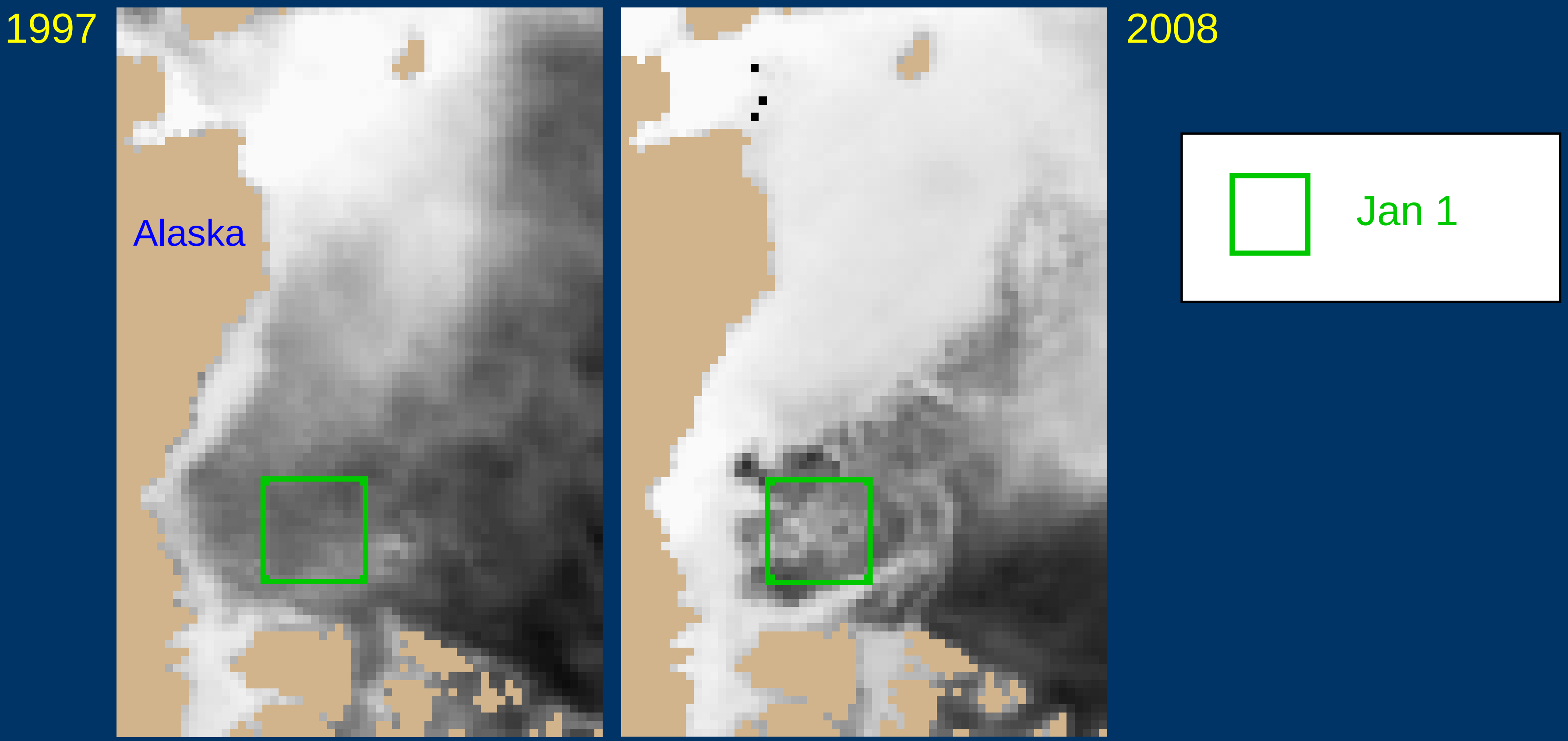
Passive microwave sea ice motion

Observed Motion vs. Free Drift Models

Instead of comparing observed motions, compare agreement between observed motion and free-drift models:

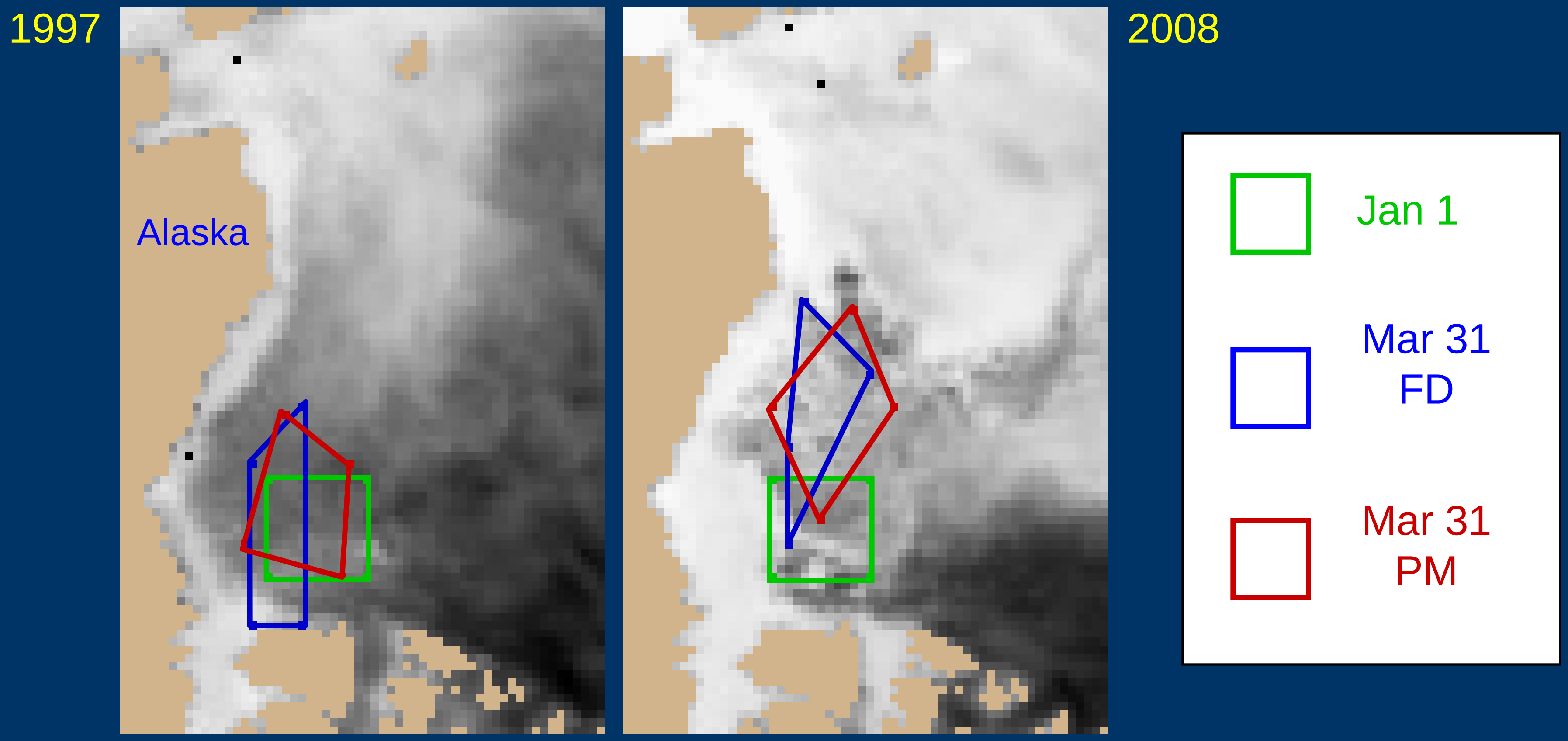
- $Ma_{ice} = \mathbf{F}_{wind} + \mathbf{F}_{current} + F_{tilt} + F_{Coriolis} + \mathbf{F}_{internal}$
- *Rule 1:* $Ma_{free\text{-}drift} \sim dp/dx * f(\Phi)$ (Zubov, 1945)
- *Rule 2:* $V_{free\text{-}drift} \approx 0.02V_{wind}$ *(30º to the right of wind) (Nansen, 1902; Ekman, 1902)*

Comparison of observed motion with free drift



37V GHz SSM/I brightness temperatures

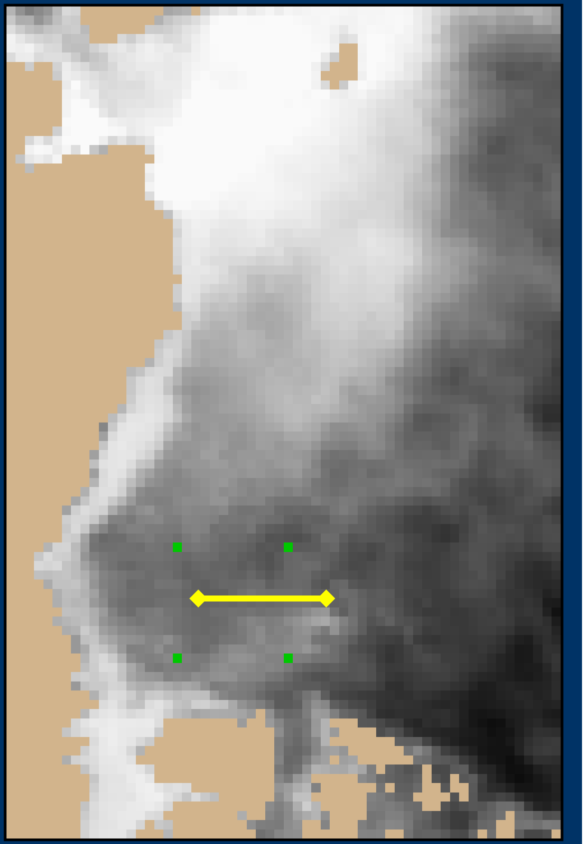
Comparison of observed motion with free drift

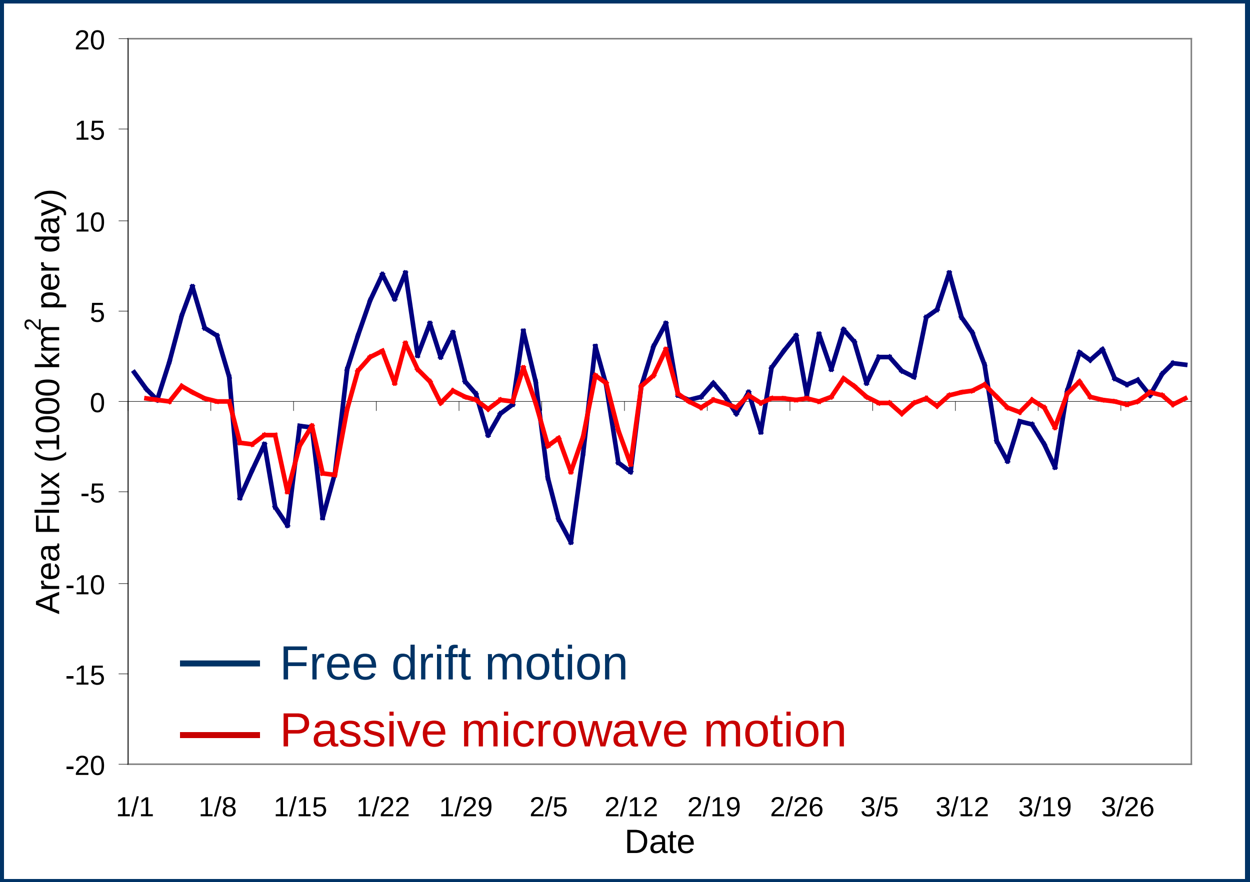


37V GHz SSM/I brightness temperatures

Area flux, 1997

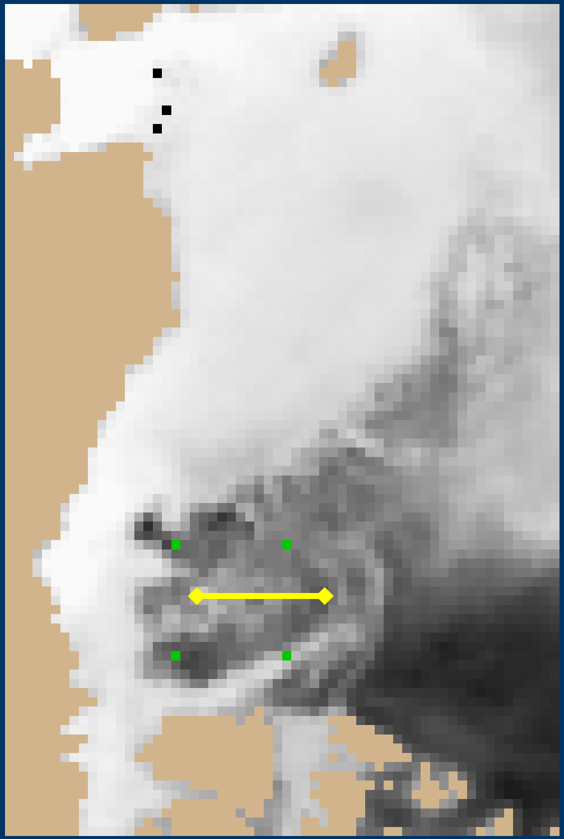
200 km wide flux gate

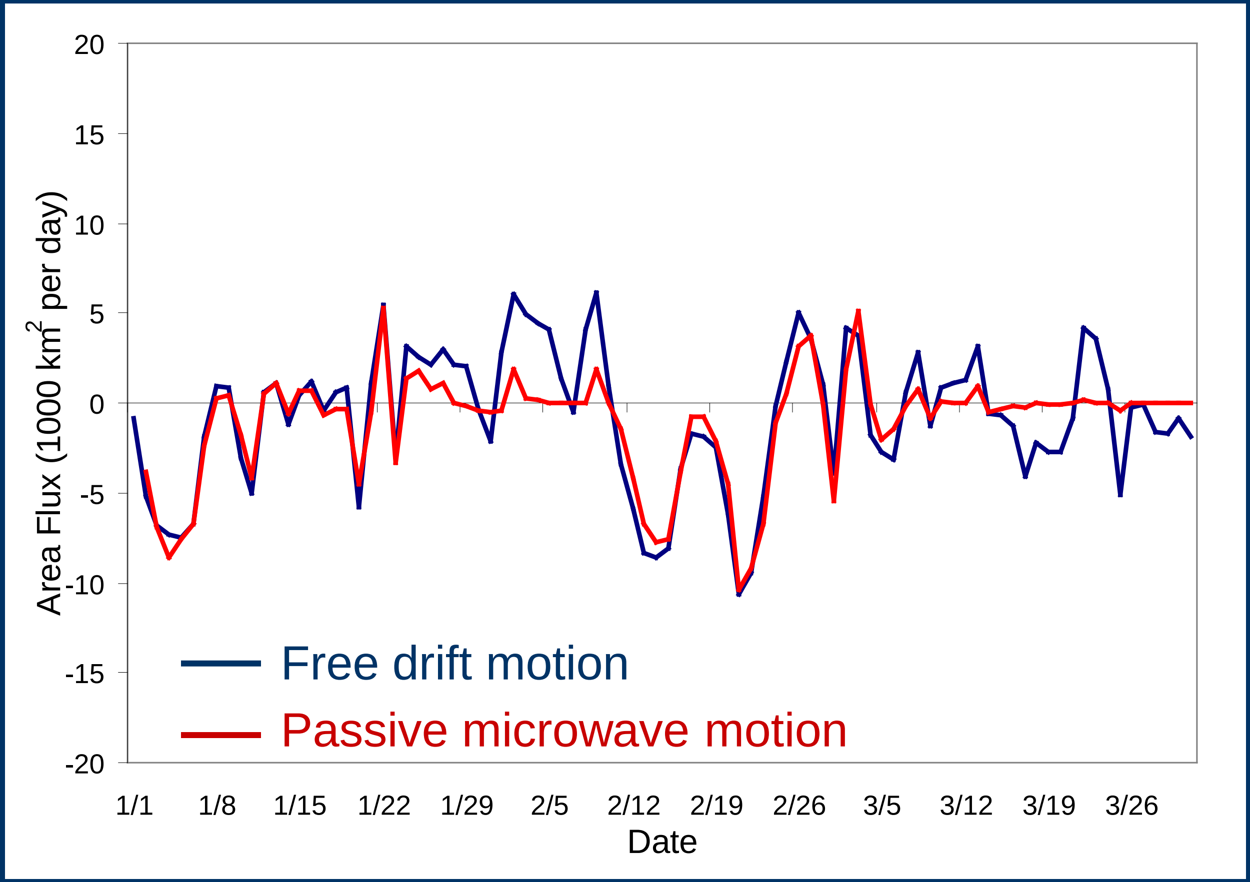




37V GHz SSM/I brightness temperatures

Area flux, 2008

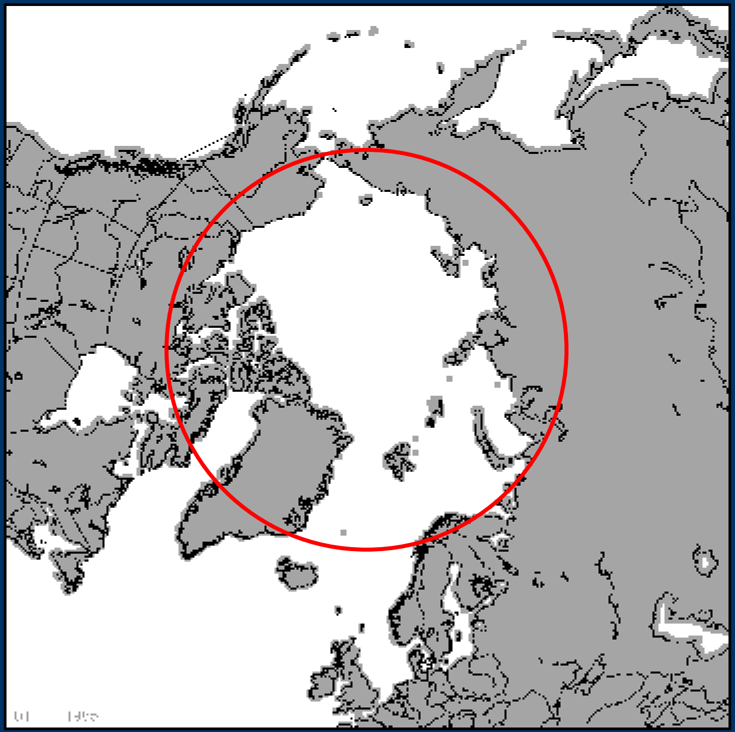




37V GHz SSM/I brightness temperatures

Basin-wide average ice motion

- Jan-Mar, 1985-2010
- North of the Arctic Circle
- Fowler/Maslanik ice motion
- NCEP surface winds
- First-year and multiyear ice age categories



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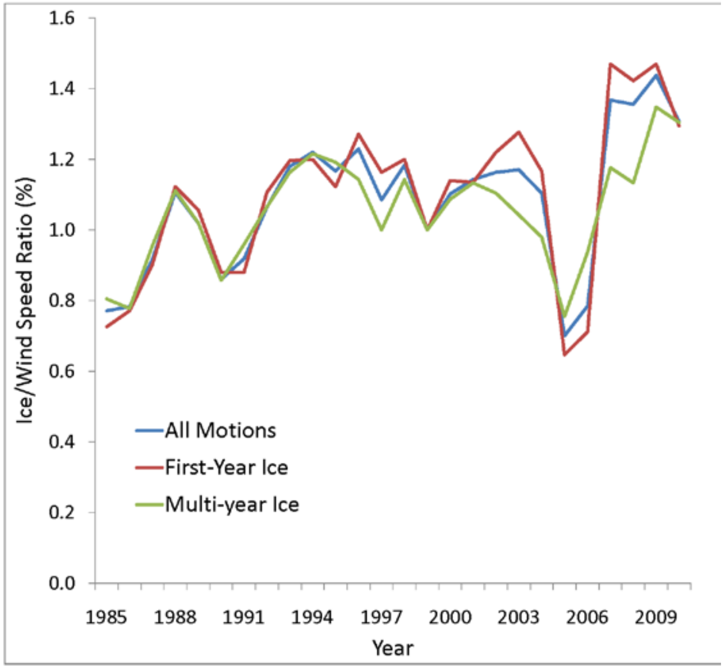
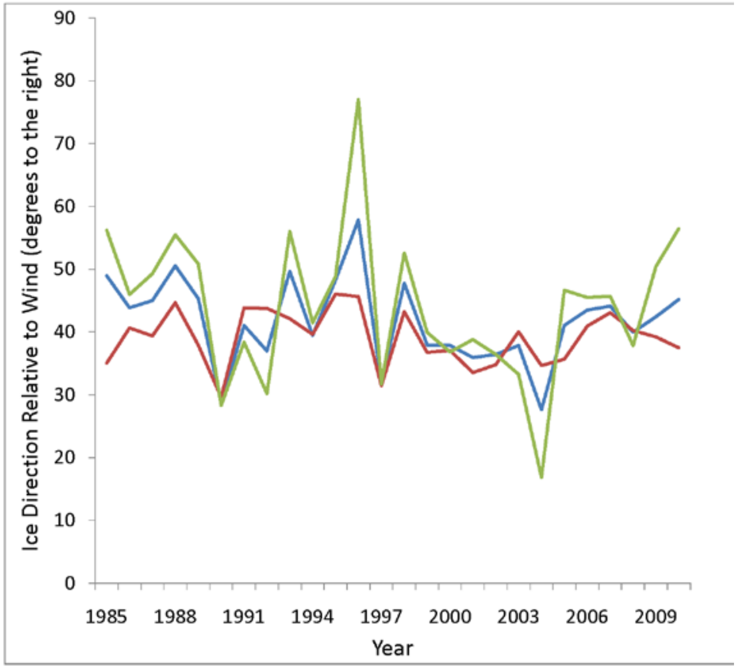
Ice Drift vs. Wind Velocities

Ice Speed Ratio



Ice-Wind Direction Diff.

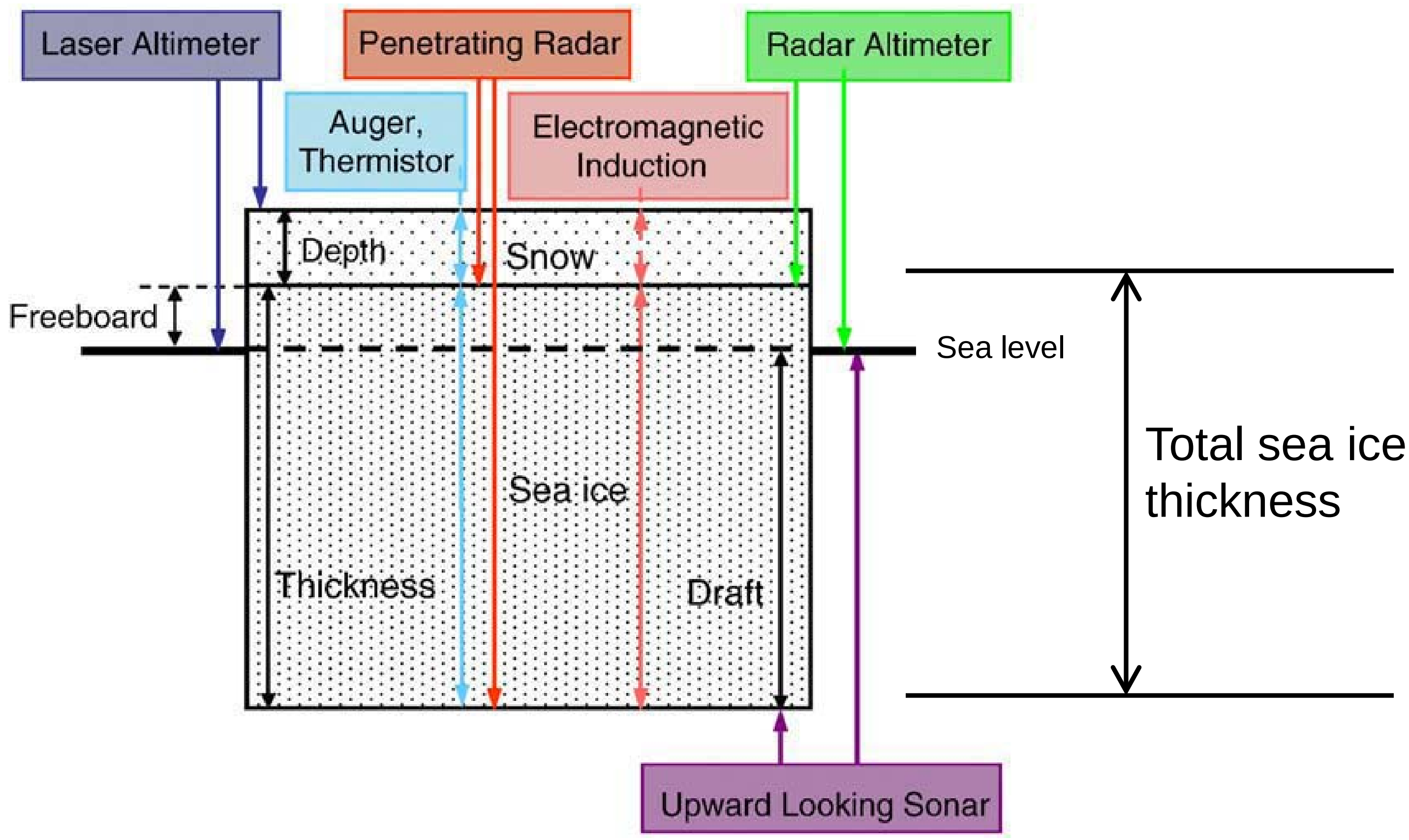


[redacted]

Sea ice thickness observations

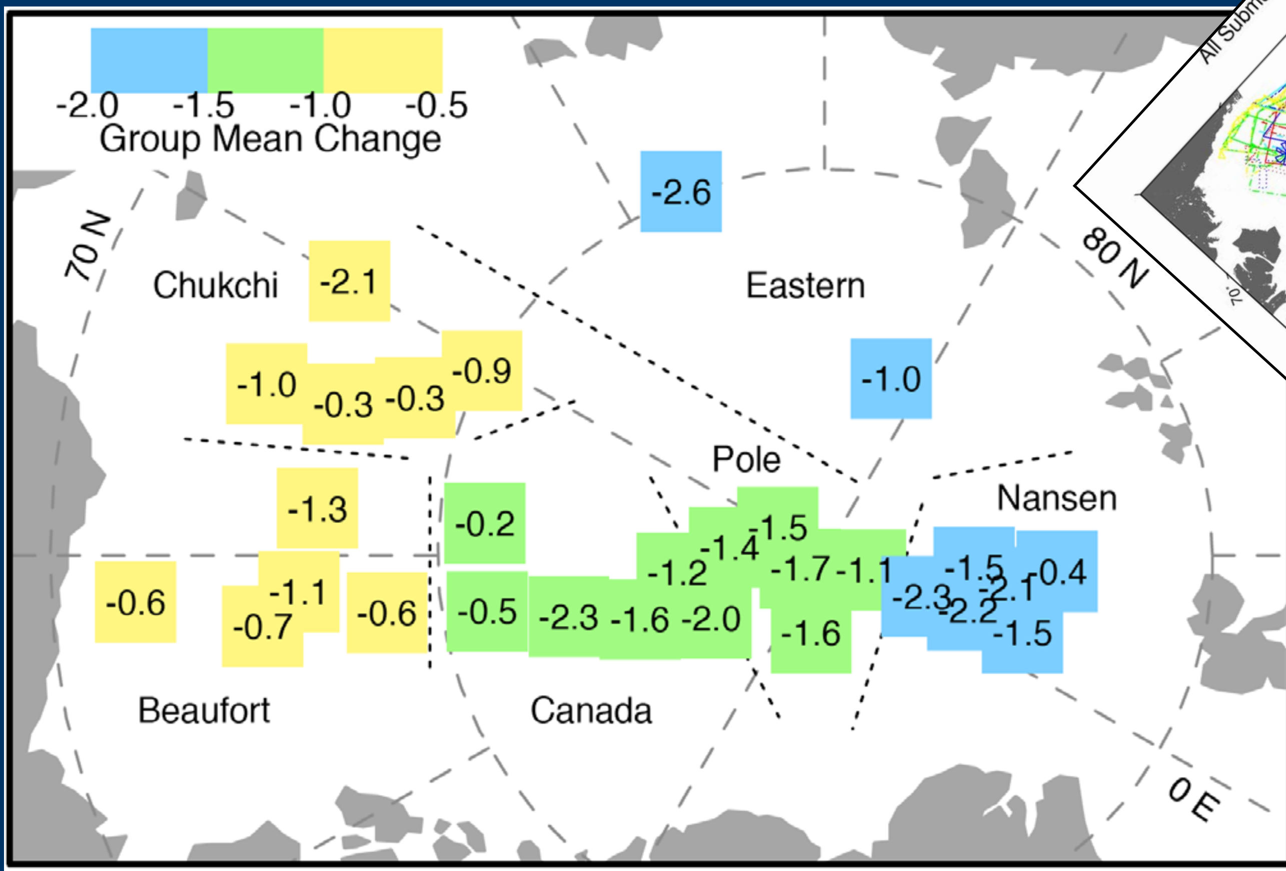
- 1950s – mid-1990s: occasional submarine data (upward looking sonar)
- Early 1990s: first satellite altimeter data over limited area of sea ice (radar altimeter)
- 2003 – 2009: NASA ICESat, regular (2-3 times per year) observation over most of sea ice (laser altimeter)
- 2010 – : ESA Cryosat-2 satellite and NASA IceBridge aircraft (radar altimeter)
- Also: in situ (drill holes) and aerial (altimeter and EM)
    - Limited regions and time periods, but more accurate
    - Valuable for calibration and validation of satellite products

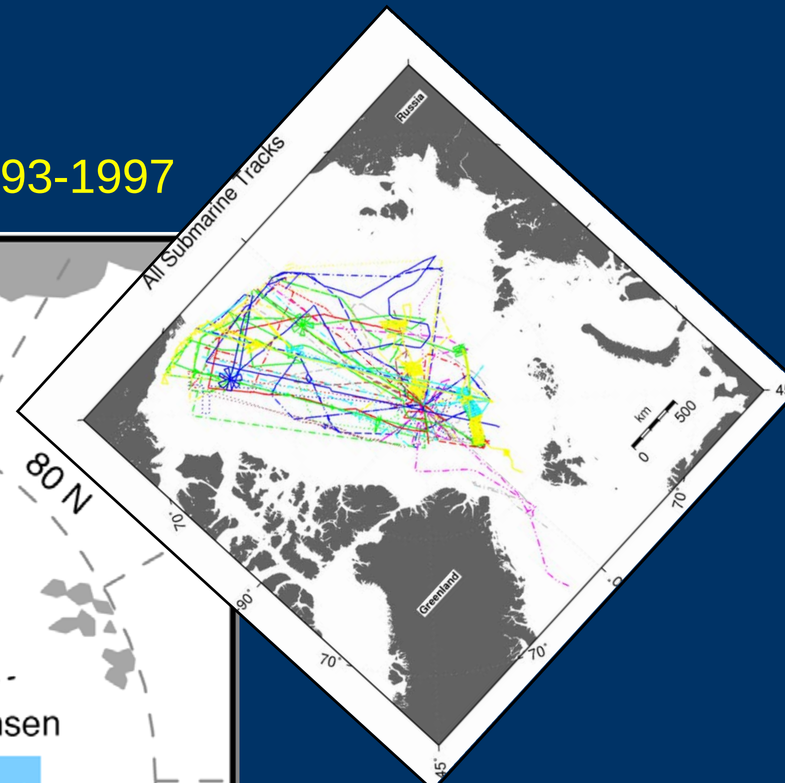
Methods for sea ice thickness observations



Ice thickness from submarines

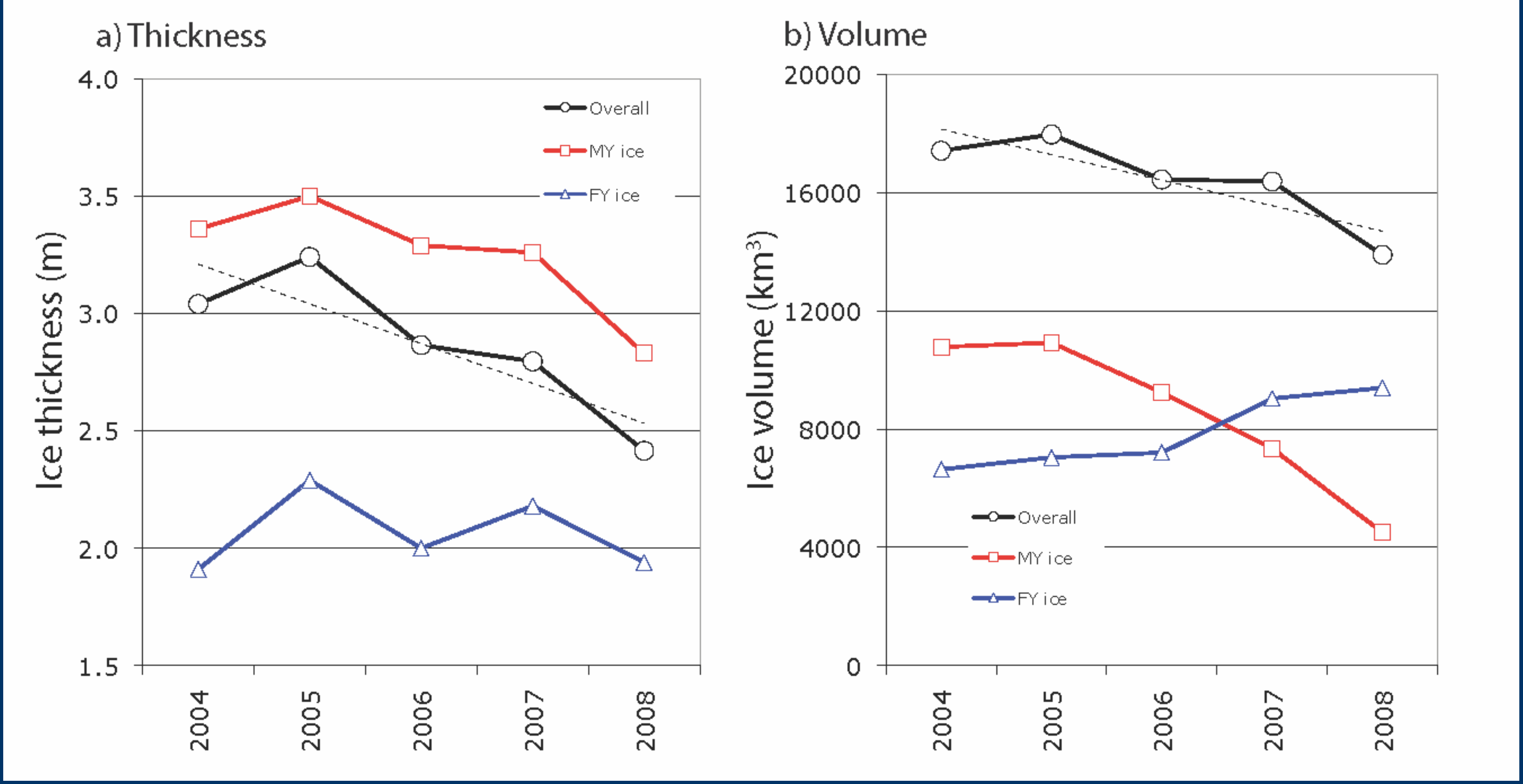
Change in thickness (m) from 1958-1976 to 1993-1997





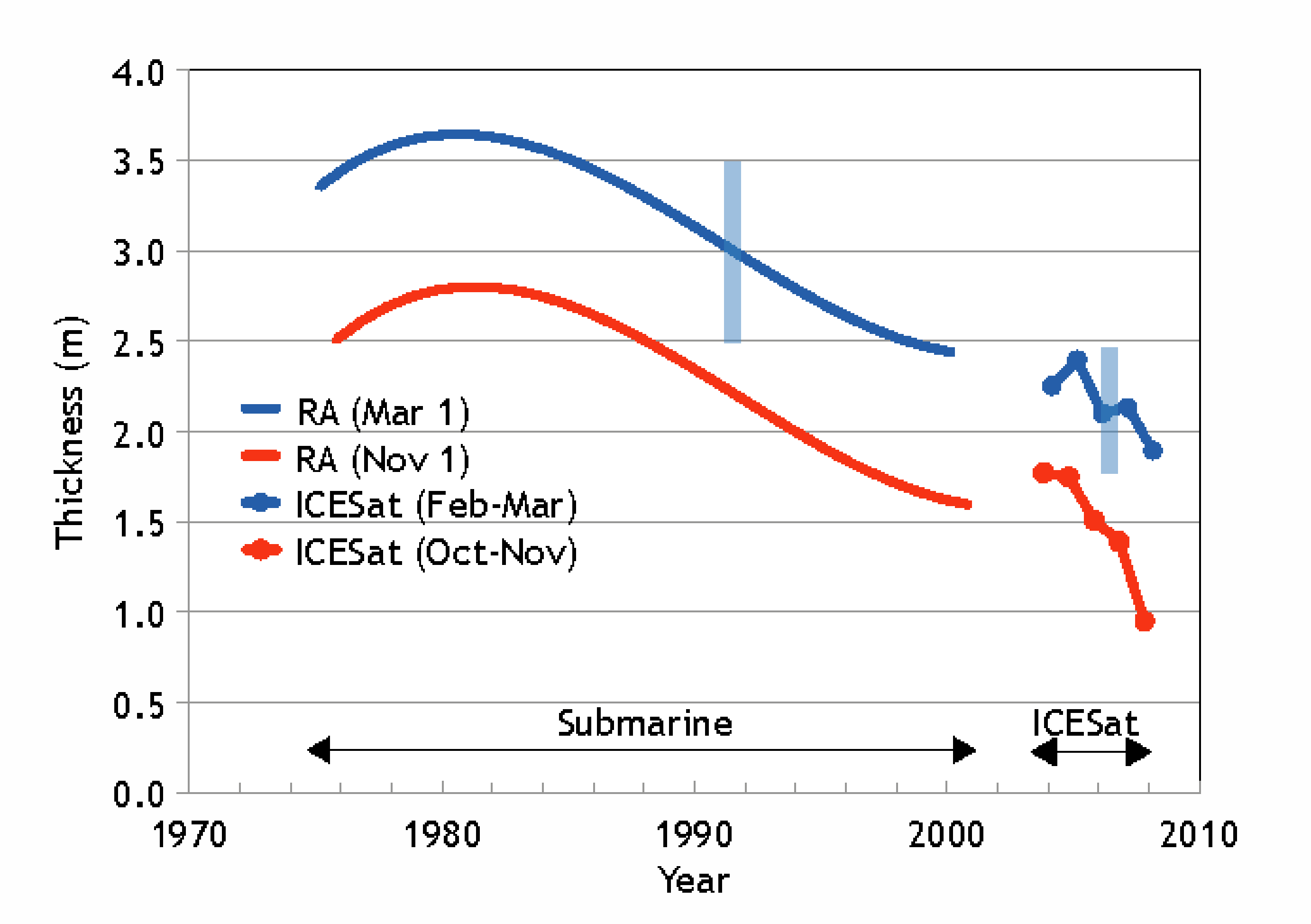
From Rothrock et al., 1999

Ice thickness from the ICESat laser altimeter



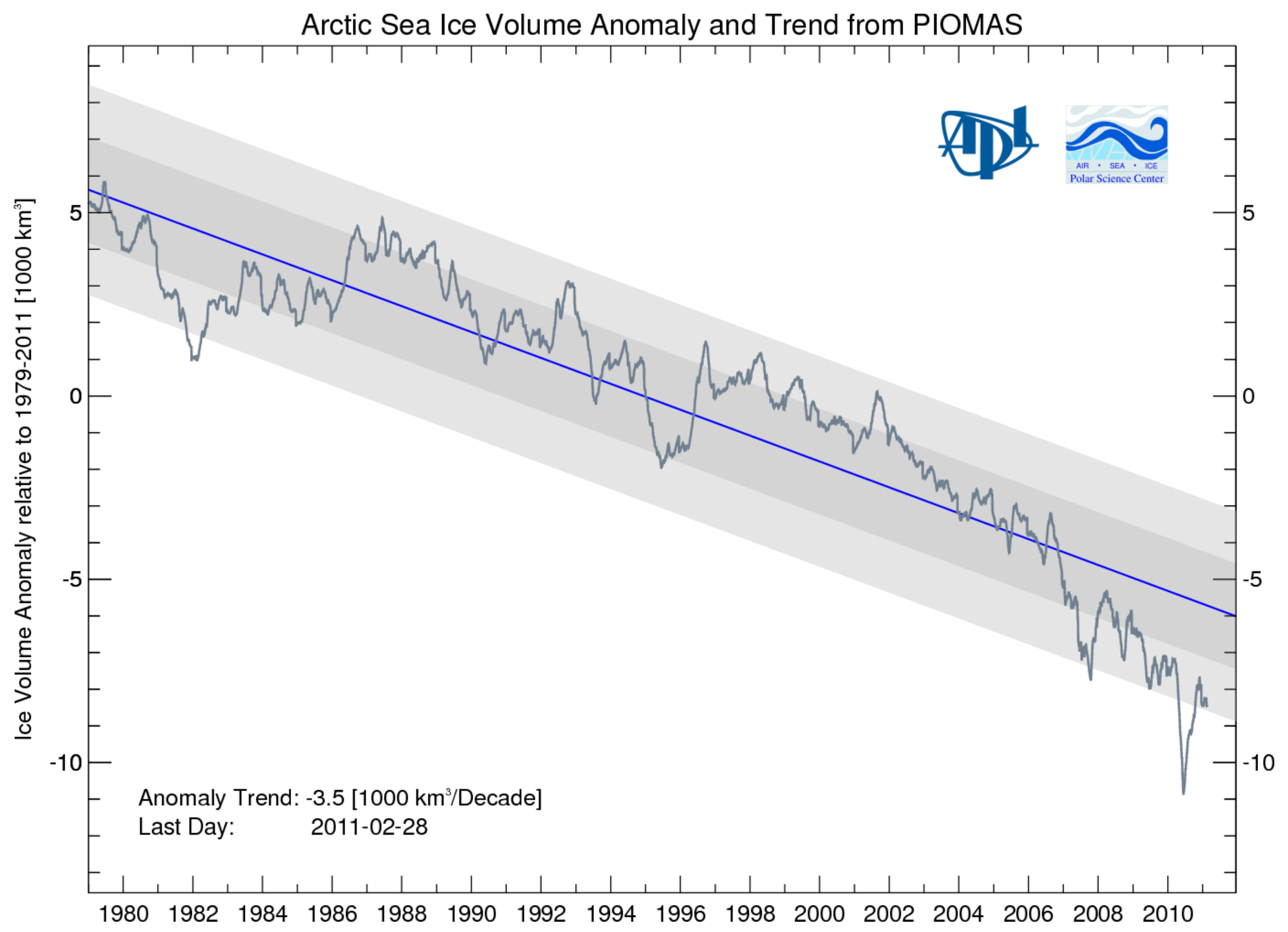
From Kwok et al., 2009

Submarine and ICESat ice thickness



From Kwok and Rothrock, 2009

Model/observation sea ice volume anomaly



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Univ. Washington Polar Science Center
http://psc.apl.washington.edu/wordpress/research/projects/arctic-sea-ice-volume-anomaly/

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Sources and References

National Snow and Ice Data Center

- http://nsidc.org
- Sea ice extent data: http//nsidc.org/data/nsidc-0051.html
- walt@nsidc.org

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Haas C, Pfaffling A, Hemdricks S, Rabenstein L, Etienne J and Rigor I. 2008. Reduced ice thickness in Arctic transpolar drift favors rapid ice retreat. Geophys. Res. Lett. 35. L17501. doi:10.1029/2008GL034457.

Kwok R, Cunningham G, Wensnahan M, Rigor I, Zwally H and Yi D. 2009a. Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. J. Geophys. Res.-Oceans. 114. C07005. doi:10.1029/2009JC005312.

Kwok R and Rothrock D. 2009b. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958 – 2008. Geophys. Res. Lett. 36. L15501. doi:10.1029/2009GL039035.

Rothrock D, Yu Y and Maykut G. 1999. Thinning of the Arctic sea-ice cover. Geophys. Res. Lett. 26. 3469-3472.

Thank You!