OCS Study BOEMRE 2011-032

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

Final Workshop Report

Contract Number: M10PC00082

Submitted to:

Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)
Alaska OCS Region
3801 Centerpoint Drive, Suite 500
Anchorage, AK 99503

Submitted by:

Science Applications International Corporation
Center for Water Science and Engineering
1710 SAIC Drive
Mclean, VA 22102

June 30, 2011

Disclaimer

This report has been reviewed by the Bureau of Ocean Energy Management, Regulation and Enforcement and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Bureau, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Contents

1.0 Task Objective

The objective of this task (Task 5 of BOEMRE Contract M10PC00082) was to develop a report that: (1) summarizes the 3 day workshop conducted from March 29-31, 2011 in McLean, Virginia, and (2) provides scientific recommendations and alternatives that BOEMRE can use as guidance for evaluating hindcast and/or forecast data in Arctic Ocean oil spill trajectory analyses. This report constitutes Deliverable 7 of Contract M10PC00082. The workshop and report were completed in partial fulfillment of the overall goal to develop scientific recommendations that BOEMRE can use as guidance to prepare projects in its study planning process. The workshop objectives to reach this goal were:

- Review the current status of oceanographic knowledge in the Arctic, including existing research in Arctic Ocean modeling and the quality of available forcing data
- Describe the attributes of hindcast data currently used for Oil Spill Risk Analysis (OSRA) and the skill assessment against observations used to evaluate the surface currents in the region
- Describe the effects of climate change on sea ice, circulation, river discharge, etc. in the Arctic Ocean and the impacts of these changes on surface circulation.
- Evaluate alternate approaches such as the incorporation of forecast modeling results in the OSRA process

2.0 Background

The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) is responsible for management of the U.S. offshore oil and gas resources including their exploration, development, production and transportation. Potential environmental and economic consequences which may result are examined and critically analyzed through the processes of environmental impact assessment and the development of alternative policies. To support this analysis, the BOEMRE plans, conducts and oversees scientific studies in all of the OCS regions.

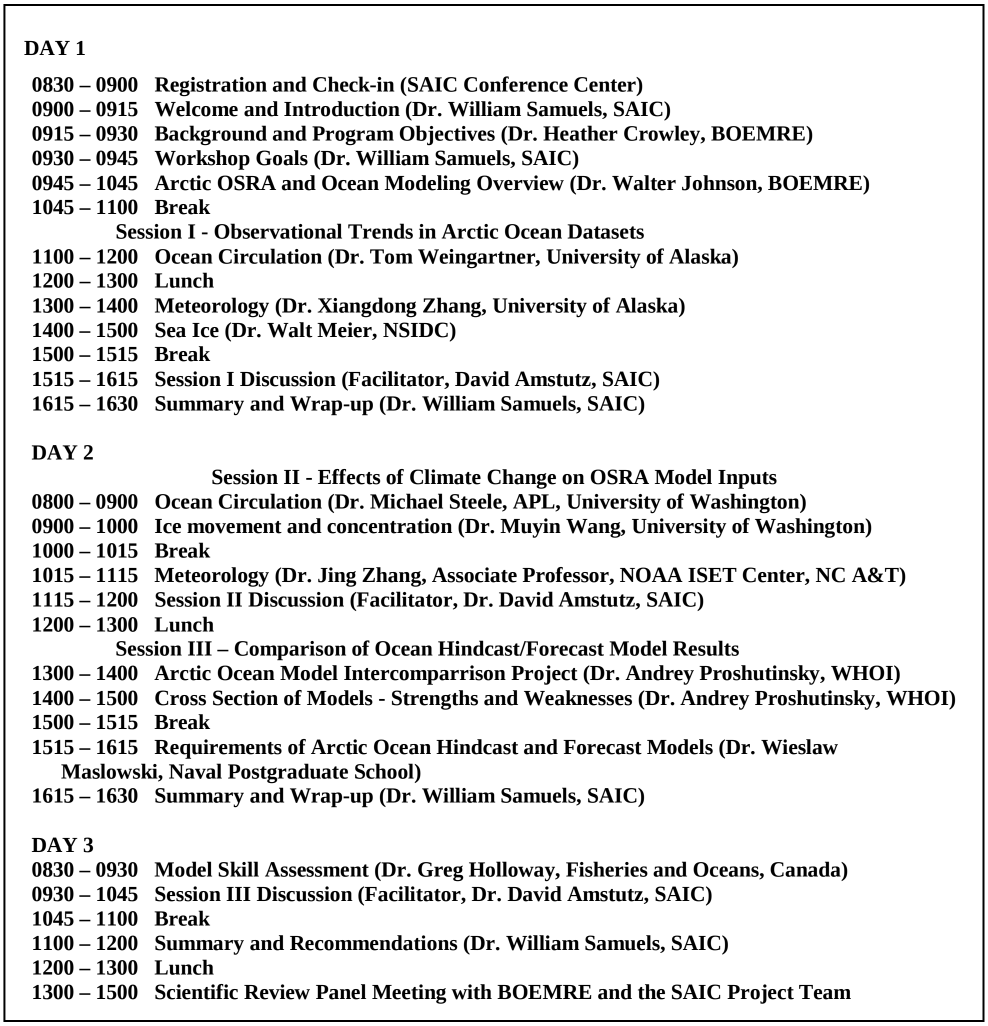
For more than thirty years the OSRA model has been used to synthesize environmental, social and economic information to produce conditional probabilities of large (≥1,000 barrels) oil spill occurrence and subsequent joint probabilities of large oil spill occurrence and contact with sensitive living and nonliving resources along the shoreline and at sea. The OSRA model produces hypothetical surface oil spill trajectories originating from exploration and production sites and transportation sites as well as from transportation routes used for imported oil. The likelihood of large oil spill occurrence is a function of well years or pipeline miles exposure, thus the benefits and consequences of producing offshore resources can be quantified using a common parameter. The OSRA model also allows for analyses of alternative production and transportation scenarios.

As reported in the literature (McPhee et al., 2009; Overland et al., 2008), recent climate variability in the Arctic Ocean has caused significant changes in the circulation of sea ice and the upper layers of the Arctic Ocean. Portions of these changes are attributable to the Arctic oscillation and some possibly to a long term warming trend. Climate prediction models forecast a dramatic decrease of Arctic sea ice including a complete loss of multi-year ice within this century. The majority of the circulation datasets used in the OSRA model do not account for these recent changes, thus there is a need to assess how forecast ice/ocean model results influence oil spill trajectories and associated risk assessments.

The BOEMRE uses surface current, ice movement and concentration, and wind data derived from ocean circulation hindcast models for oil-spill trajectory calculations used in lease sale National Environmental Policy Act (NEPA) documents. The Oil-Spill-Risk Analysis estimates risk over the life of hypothetical oil fields resulting from oil and gas lease sales, typically 20-25 years into the future. The OSRA is also used for Development and Production Plans, when the location of the actual development is known. Oceanic current patterns in the Arctic, especially in near shore regions, are strongly influenced by climatological factors such as winds, precipitation minus evaporation, river runoff and sea ice type and extent. In addition, for the Chukchi Shelf, the Bering Strait inflow is also important. The rapid changes in each of these factors that are now occurring could lead to drastic alterations of the surface current fields. New datasets of modeled surface currents, winds and ice concentration for use in OSRA will be delivered in 2012. Because of the pace at which conditions are changing and sea ice is being lost in the Arctic summer, BOEMRE needs to assess whether forecast ice/ocean model results might contain useful information for the purposes of OSRA oil spill trajectory estimation. The use of forecast model results could give guidance about the effects of changes in wind direction and ice/ocean motions under reduced summer ice conditions. This must be balanced by the requirements that ice/ocean model results be compared to observations.

3.0 Workshop

A three day workshop was held at the Science Applications International Corporation (SAIC) Conference Center in McLean, Virginia from March 29-31, 2011. The workshop covered four main topics (see figure 1): (1) Arctic OSRA and Ocean Modeling Overview, (2) Observational Trends in Arctic Ocean Datasets, (3) Effects of Climate Change on OSRA Model Inputs and (4) Comparison of Ocean Hindcast/Forecast Model Results. Each session consisted of three presentations followed by a discussion. Session sub-topics included ocean circulation, sea ice, meteorology, and modeling issues such as skill assessment, strengths and weaknesses, and model comparisons.



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, NSIDC)**
1500 – 1515	**Break**
1515 – 1615	**Session I Discussion (Facilitator, David Amstutz, SAIC)**
1615 – 1630	**Summary and Wrap-up (Dr. William Samuels, SAIC)**
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, Associate Professor, NOAA ISET Center, NC A&T)**
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)**
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**

Figure 1. Workshop agenda.

A total of 25 individuals participated in the workshop representing the Federal Government, academia, the oil industry and private industry (see Appendices A and B respectively for a list of the workshop attendees and speaker bios). A summary of the workshop presentations is provided below. This is followed by a section on recommendations discussed at the workshop by the attendees and the Scientific Review Panel (Dr. CJ Beegle-Krause, Dr. Andrey Proshutinsky and Dr. Tom Weingartner). Complete workshop presentations are contained in a separate Appendix and can be downloaded at http://alaska.boemre.gov/ref/Presentations/presentations.htm.

3.1 BOEMRE Alaska OCS and OSRA Background

3.1.1 BOEMRE Environmental Program – Dr. Heather Crowley

The BOEMRE Environmental Studies Program was established and funded by the United States Congress to support the Outer Continental Shelf (OCS) offshore oil and gas leasing program of the U.S. Department of the Interior (USDOI) in pursuit of national energy policies. The Outer Continental Shelf Lands Act (OCSLA) of 1953, as amended (43 U.S.C. 1331 et seq.), provides guidelines for implementing an OCS oil and gas exploration and development program based on the need to balance orderly energy resource development with protection of the human, marine, and coastal environments. The basic mission of BOEMRE is to expedite mineral resource exploration and development at fair market value in an environmentally safe and responsible manner.

The Environmental Studies Program (ESP) operates on a national scale to assist in predicting, projecting, assessing and managing potential effects on the human, marine and coastal environments of the OCS that may be affected by oil and gas development (see figure 2). Lease-management decisions are enhanced when current, pertinent and timely information is available. Final reports from the ESP are most directly utilized by teams of NEPA analysts within the BOEMRE Environmental Analysis Sections when they prepare and/or review Environmental Impact Statements (EISs), Environmental Assessments (EAs), Exploration Permits, and Development and Production Plans. The ESP manages ongoing study projects in Alaska (currently about 45 – see research questions below) in disciplines such as physical oceanography, fate and effects of pollutants, protected and endangered species, wildlife biology, and the social sciences.

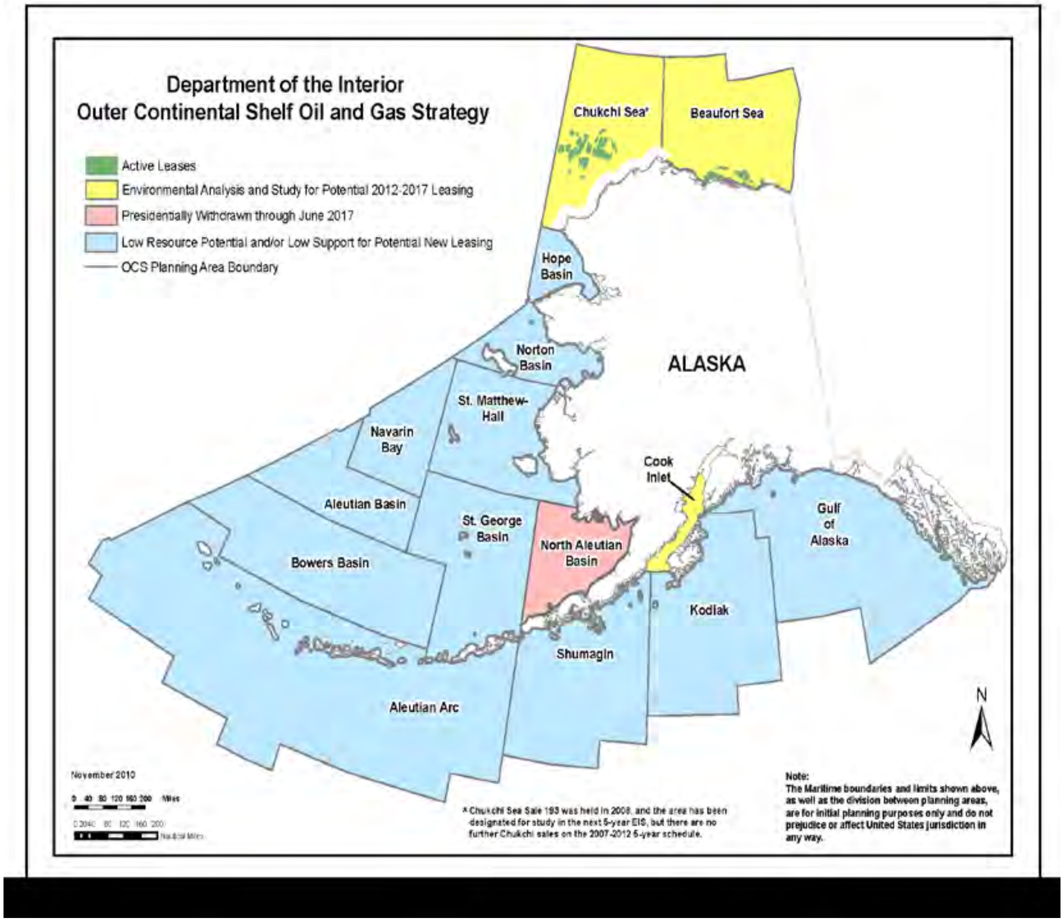


Figure 2. Map of Alaska OCS Planning Areas.

Current offshore oil and gas-related issues addressed by ongoing and proposed studies in the Beaufort Sea and the Chukchi Sea include but are not limited to (BOEMRE, 2010):

- What refinements are there to our knowledge of major oceanographic and meteorological processes and how they influence the human, marine and coastal environment?
- What role will currents play in distribution of anthropogenic pollutants near development prospects?
- What long-term changes in heavy metal and hydrocarbon levels may occur near Beaufort Sea development prospects, such as Liberty, or regionally along the Beaufort Sea coast?
- How do we improve our model predictions of the fate of potential oil spills?
- If oil is spilled in broken ice, what will its fate be?

- What effects might pipeline construction have on nearby marine communities or organisms?

- What changes might occur in sensitive benthic communities such as the Stefansson Sound “Boulder Patch,” and other Beaufort Sea kelp communities or fish habitats?

- What are the current spatial and temporal use patterns of these planning areas by species that are potentially sensitive, such as bowhead whales, polar bears, other marine mammals, seabirds and other birds, or fish?

- What is the extent of endangered whale feeding in future proposed or potential lease sale areas?

- What changes might occur in habitat use, distribution, abundance, movement or health of potentially sensitive key species such as bowhead whales, polar bears, other marine mammals, seabirds and other birds, or fish?

- What interactions between human activities and the physical environment have affected potentially sensitive species?

- What changes might occur in socioeconomics and subsistence lifestyles of coastal Alaska communities?

- What are current patterns of subsistence harvest, distribution and consumption and what changes might occur in key social indicators as a result of offshore exploration and development?

- How can we continue to integrate local and/or traditional knowledge into studies related to the Alaska ESP?

3.1.2 Oil Spill Risk Analysis Introduction – Dr. Walter Johnson

The BOEMRE assesses oil-spill risks associated with offshore energy activities off the U.S. continental coast and Alaska by calculating spill trajectories and contact probabilities. These analyses address the likelihood of large oil spill occurrences, the transport and fate of any spilled oil, and the environmental impacts that might occur as a result of the spill. The BOEMRE Oil-Spill Risk Analysis (OSRA) model combines the probability of large oil spill occurrence with a statistical description of hypothetical oil-spill movement on the ocean surface (BOEMRE, 2011).

Modeling results are used by BOEMRE staff for preparation of environmental documents in accordance with the National Environmental Policy Act; other Federal and State agencies for review of environmental impact statements (EISs), environmental assessments, and endangered species consultations; and oil industry specialists preparing the oil spill response plans (see figure 3) .

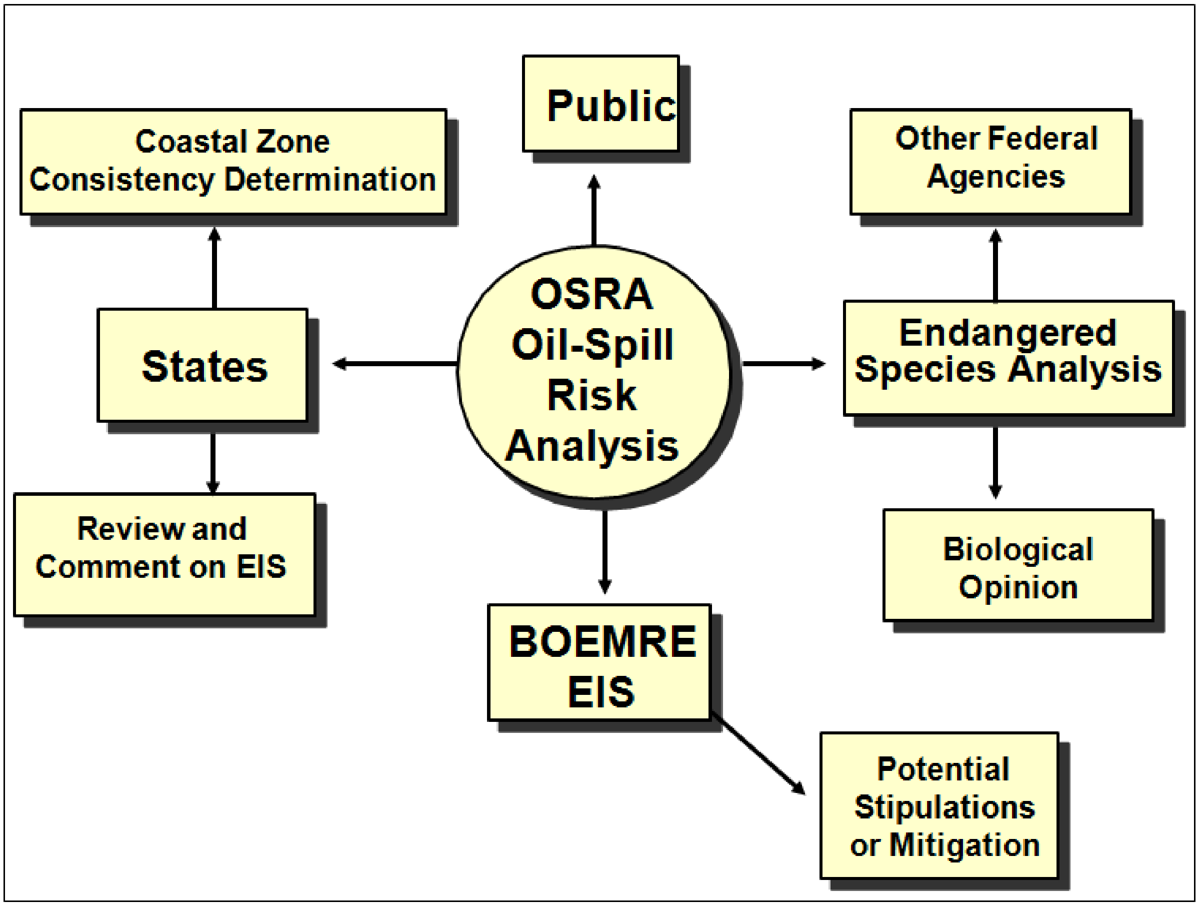


Figure 3. BOEMRE Oil Spill Modeling Program.

Paths of hypothetical large oil spills are based on hindcasts (history) of winds, ocean currents, and ice in Arctic waters, using the best available input of environmental information. Outputs of the model include tables of probable contact and GIS (Geographic Information System) representations of these probabilities, with and without the probability of the occurrence of one or more large spills (see figure 4).

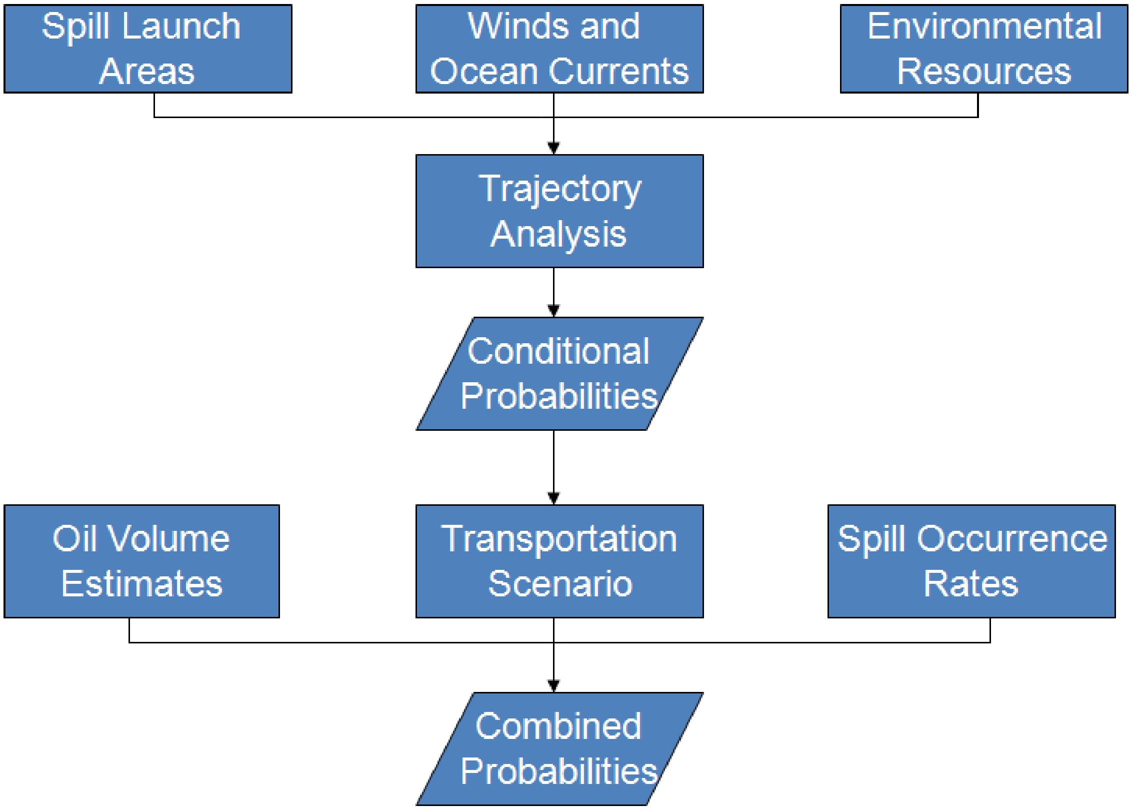


Figure 4. OSRA Modeling Process.

In the Alaskan Arctic, the OSRA Model is run for the Beaufort and Chukchi Seas (see figure 5). The model study area extends beyond the proposed leasing, exploration or development area to adequately represent environmental, social or economic resource areas that could potentially to be affected. The base map boundaries are usually chosen so that the lease sale or development area is centered. Data required within the study area include:

- 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
- Wind
    - Satellite-based product, TOVS Pathfinder

- Landfast Ice Zone Mask, seasonal
- Ocean Currents – Ice Motion
    - Rutgers University Coupled Ice/Ocean Model results (Hedstrom, 2009)
    - Daily intervals
    - Curvilinear grid

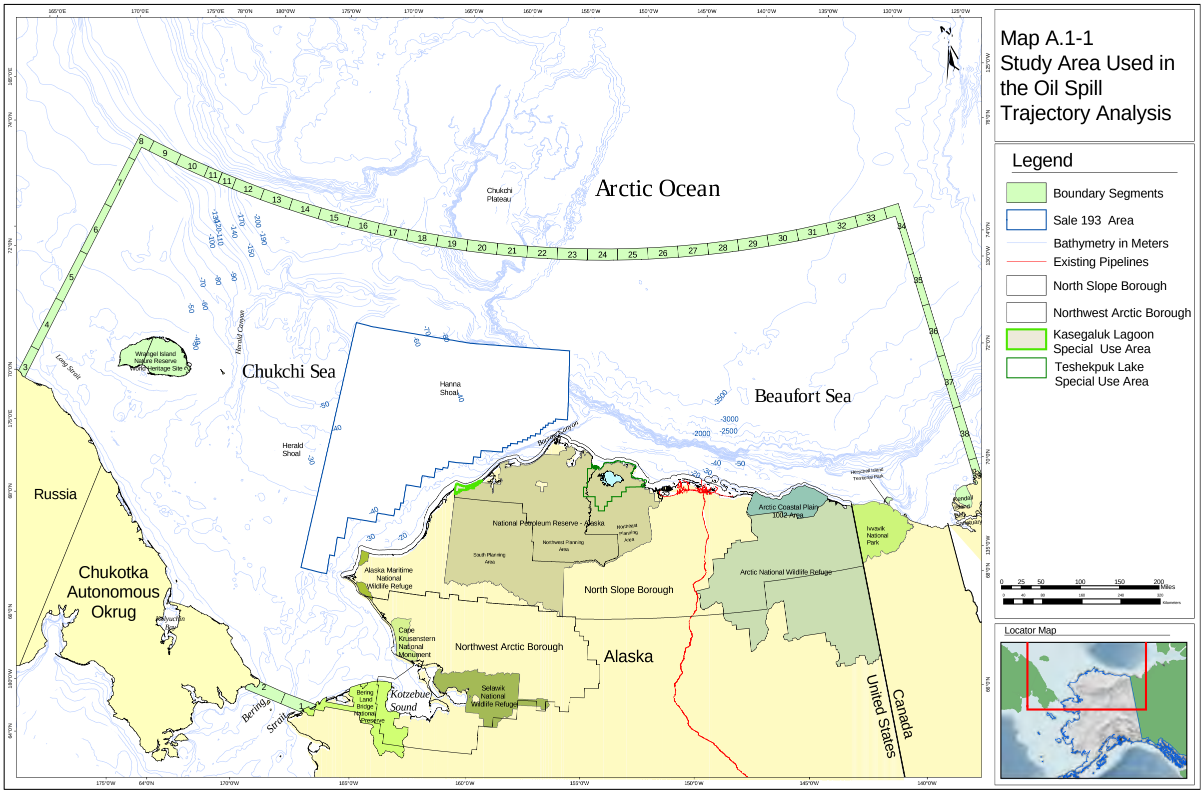


Figure 5. Study area used in the Oil Spill Risk Analysis for the Alaskan Arctic region.

In OSRA, 2.7 million trajectories are simulated (2700 from each hypothetical spill point) and contacts are tabulated for: (1) boundary segments, (2) environmental resource areas or (3) land segments. A special algorithm is implemented for oil in the moving pack ice, oil moves with the ice for concentration ≥80% ice. The results are tabulated for time intervals, 3-, 10-, 30-, 60-, 180-, and 360-days.

OSRA is stochastic – probabilities are based on simulations of ice and ocean vectors generated by ocean circulation models and wind and spill occurrence records. OSRA 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 and, how spilled oil weathers.

3.2 Observational Trends in Arctic Ocean Datasets

3.2.1 Ocean Circulation – Dr. Tom Weingartner

In the Chukchi and Beaufort Seas, global processes drive the Pacific and Atlantic inflows and the Beaufort Gyre. Both shelves communicate with one another and have linkages with the Basin via the shelf break: up/downwelling and “eddy” exchanges, East Siberian Sea and Mackenzie/Beaufort shelf (see figure 6).

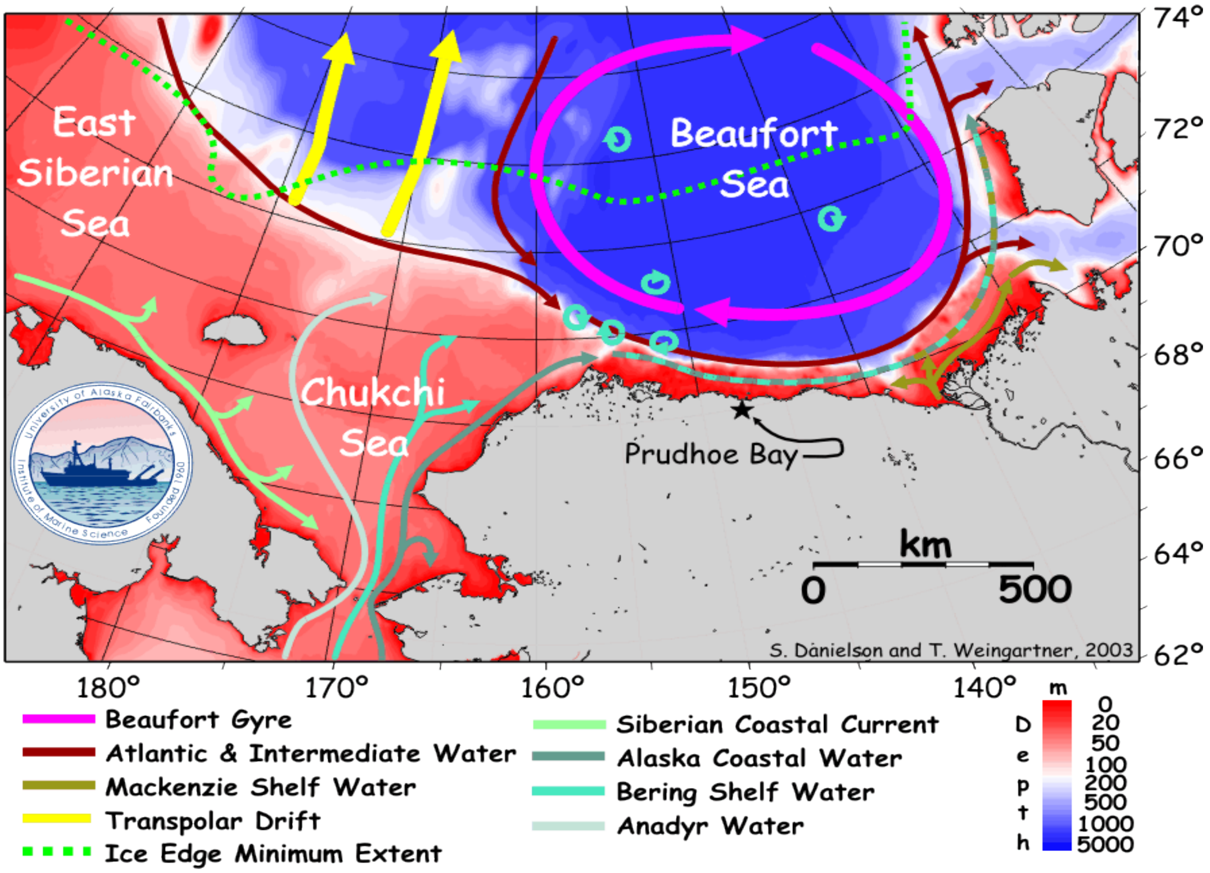


Figure 6. The Chukchi/Beaufort regional setting.

In the Chukchi Sea, the mean flow is northward, bathymetrically “steered”, and opposes the wind. The transit time from the Bering Strait to Barrow Canyon during the summer is ~3 months; and during winter are from 6 – 9 months at least (see figure 7). Shoals are isolated "trapping" zones of sea ice and the circulation. The western and central Chukchi shelf feeds the eastern shelf and Barrow Canyon. Shelf break flow is intensified north of Hanna Shoal, where the shelf break isobaths converge. The shelf is stratified from spring through fall although the stratification varies spatially. Subsurface current strength is proportional to bottom slope (~0.5 m/s in Barrow Canyon, ~0.2 m/s in Central Channel, and ~<0.1 m/s elsewhere). Wind-forced variability is ~50% of current variance with current coherence scales being ~300 km or more. Currents fluctuate along-isobaths with maximum variance in winter and minimum variance in summer.

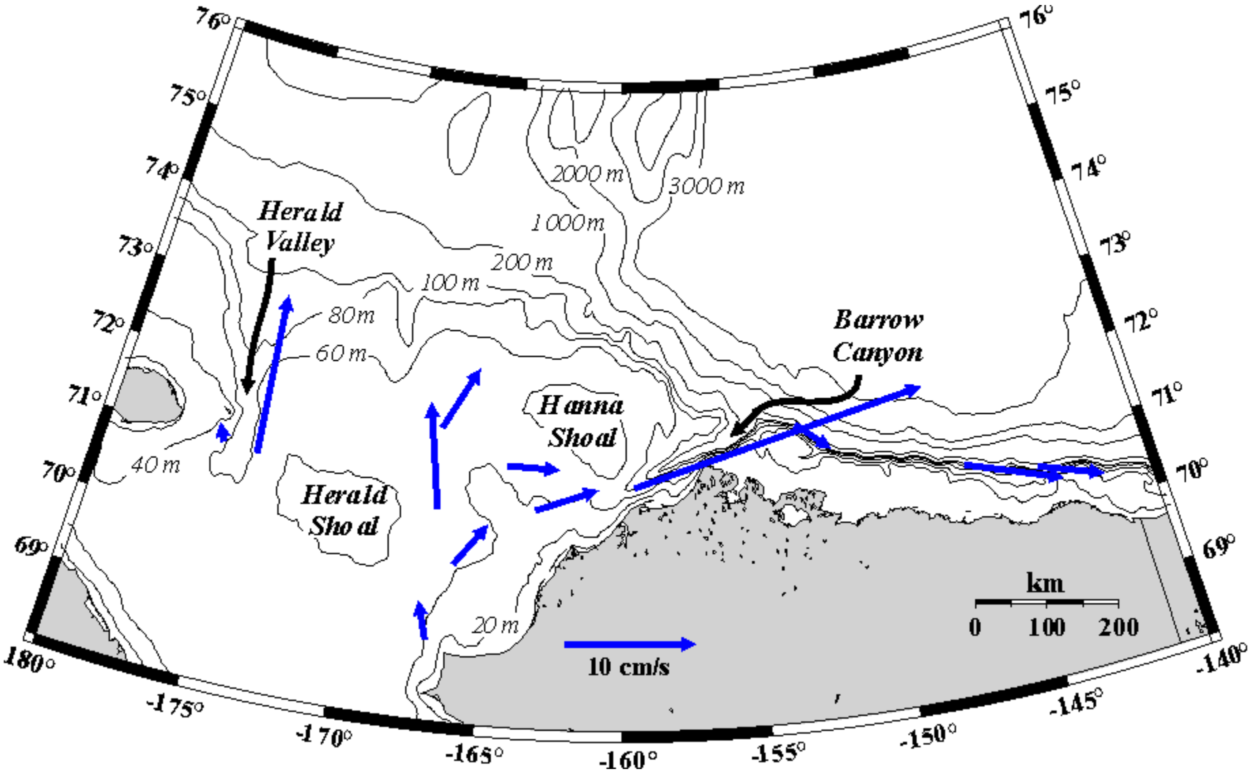


Figure 7. Composite Mean Flow Field from Sub-surface Measurements (1990 – 1995)

In summary, the Chukchi Shelf can be characterized as follows:

- Properties (dynamic and water masses) largely controlled by the Bering Strait (Woodgate et al, 2005).
- Bathymetry is key to spatial variability
- NE Chukchi Sea (subsurface) waters flow toward Barrow (shelf break)

- Hanna Shoal region may be a trapping or recirculation zone.
- Surface and sub-surface flow may differ (winds and stratification).

Over the Alaskan Beaufort Shelf, properties and dynamics are set by the lateral, oceanic (shelf break), and coastal boundaries, and the freeze/thaw cycle. The shelf is bathymetrically smooth and rivers discharge to the central and eastern Beaufort (see figure 8).

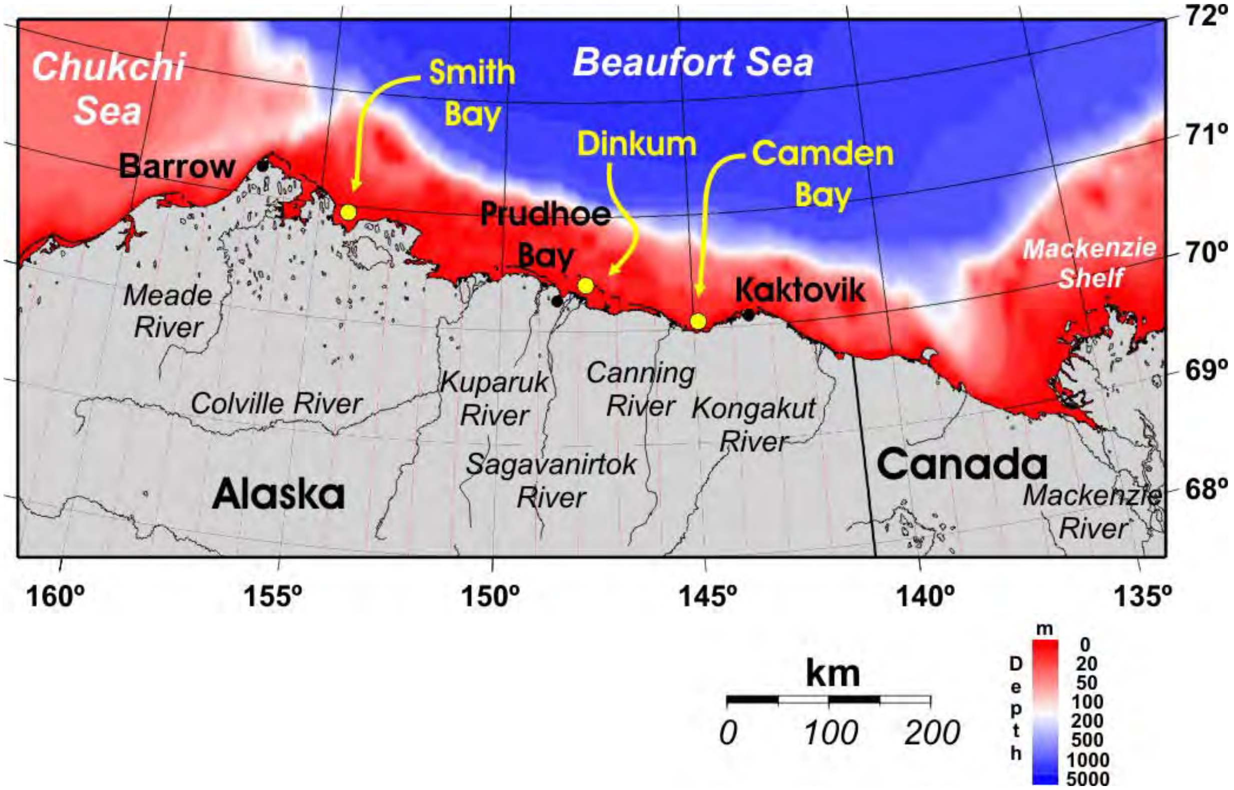


Figure 8. Map of the Alaskan Beaufort Sea.

At the oceanic boundary, the shelf break controls the shelf/basin exchange. Mean eastward flow within the cold upper halocline is centered at ~100 m, is 15 km wide, and includes “Chukchi winter water” (T < -1C; 32.5 < S < 33.5). Landfast ice occupies 20% of the shelf. For “open water”/“drifting ice”, current speeds are 10 - 50 cm-s^{-1} with alongshore coherence scales of ~300 km (correlated with winds). For landfast ice, winter current speeds are ~<5 cm-s^{-1}, uncorrelated with local or remote winds and have alongshore coherence scales of ~100 km (). These differences are because landfast ice is essentially immobile and does not transmit atmospheric momentum directly to the ocean. Moreover, spatial variations in the ice-ocean friction, r_{ice} (due to underice topography) and/or alongshore variations in landfast ice width leads to small decorrelation length scales. In summary the Alaskan Beaufort Shelf can be characterized as follows:

- Spatially complex due to boundaries :
  - Chukchi, coastal, “oceanic”, Mackenzie Shelf and pack/landfast ice
- Seasonality associated with freeze/thaw cycle;
  - seasons change abruptly (within days!)
- Landfast ice:
  - dynamics are poorly understood;
  - converts large scale wind-forcing into small-scale ocean circulation patterns

3.2.2 Beaufort/Chukchi Seas Surface Wind Climatology, Variability, and Extremes: Data Analysis and Model Simulation – Dr. Xiangdong Zhang

The surface wind field is a critical input for driving ocean currents and dispersion of potential oil spills. In particular, extreme winds can occur in association with intense mesoscale weather systems, causing a sudden change of wind direction and wind speed, coastal flooding and erosion, wave surges, and infrastructure breakdowns. This presentation covered three major topics regarding the Beaufort/Chukchi Seas surface wind climatology, variability and extremes:

- The role of large scale atmospheric circulation’s control:
  - Leading models explain approximately 20-35% of the observed variance
  - These models provide initial conditions (IC) and boundary conditions (BC) to regional/mesoscale models
- Description of regional and finer scale features:
  - highly variable wind speed and direction
  - local dynamic and thermodynamic effects
- Analysis of mesoscale modeling and data assimilation:
  - Develop realistic, high resolution data
  - Understand regional variability and change

Large scale atmospheric control plays an important steering role in the surface wind field (see figure 9) and consequently impacts the underlying sea ice and ocean. However, surface wind has its own complex and regional features and influences local as well as large scale sea ice and ocean processes. The atmospheric circulation pattern has radically shifted and rapid systematic changes have occurred since the late 1990s (see figure 10).

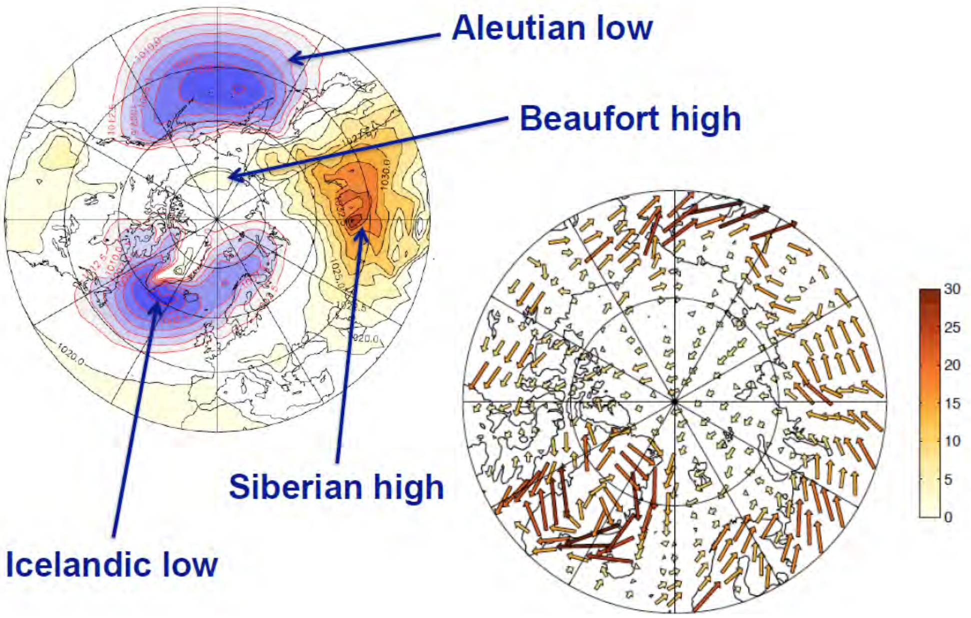


Figure 9. Climatology of surface atmospheric circulation: sea level pressure and surface wind stress.

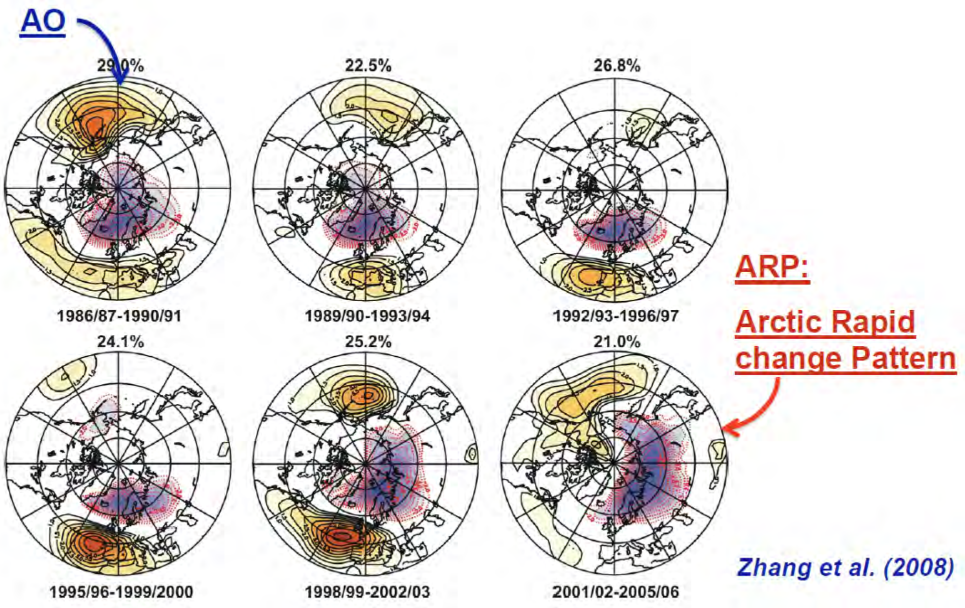
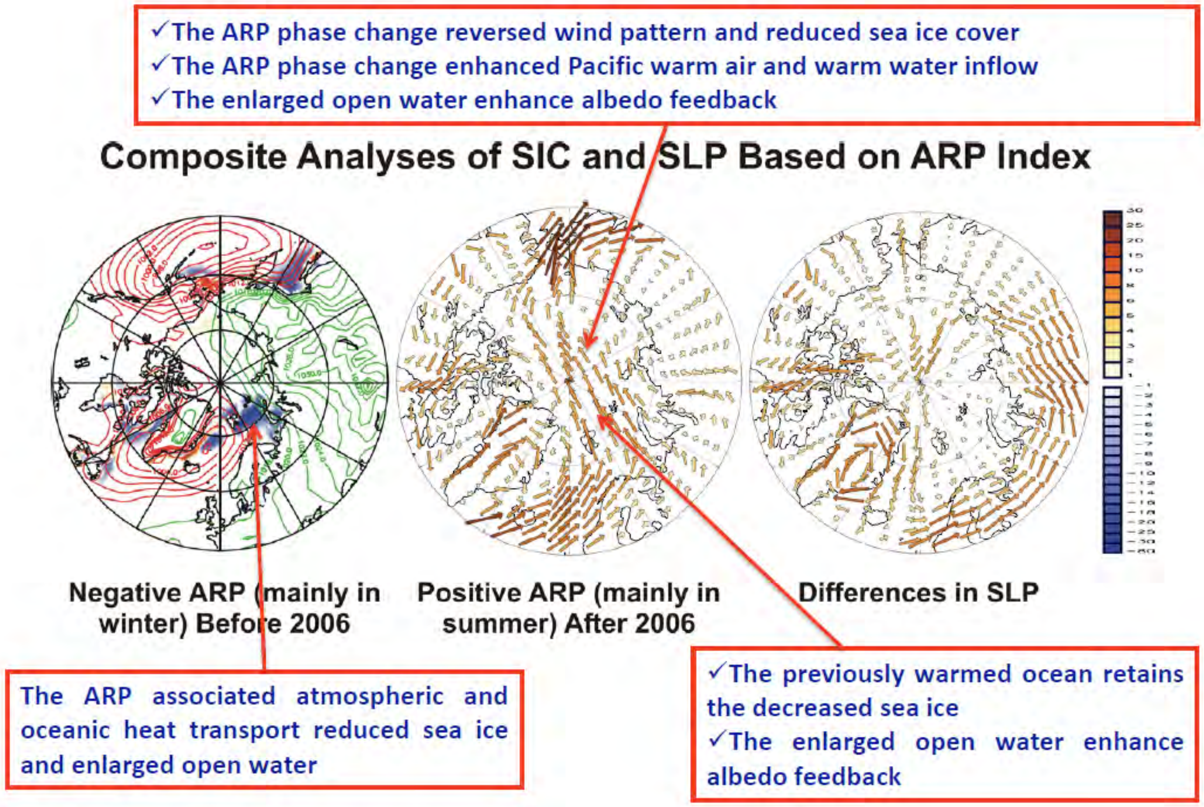


Figure 10. Changes in the atmospheric circulation pattern in the Arctic.

The Arctic Rapid change Pattern (ARP) steered surface wind and its polarity and a swift phase transition caused extreme sea ice loss in the summer of 2007 (see figure 11).



✓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

Figure 11. Composite analyses of sea ice concentration (SIC) and sea level pressure (SLP on the Arctic Rapid change Pattern (ARP) index.

In summary, 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. 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. Mesoscale modeling shows improved representation of finer scale meteorological systems and processes, helping to better understand regional wind variability and change. This in turn, provides improved simulations of ocean, sea ice and oil dispersion. Important issues regarding mesoscale modeling are:

- 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

3.2.3 Arctic Sea Ice Observations – Dr. Walt Meier

The National Snow and Ice Data Center (NSIDC) is part of the Cooperative Institute for Research in Environmental Sciences (CIRES) -- a partnership between a university research organization and NOAA's Office of Oceanic and Atmospheric Research (OAR). NSIDC data includes sea ice extent and concentration observations as follows:

- 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

In collaboration with the NOAA National Ice Center, CIRES also provides access to Multi-sensor Analyzed Sea Ice Extent (MASIE-NH) which reports daily ice edge at a 4 km resolution. MASIE-NH uses best input available (SAR, Vis/IR, Hi-res PM) and human analysis.

Through the examination of satellite records there is a significant downward trend in Arctic sea ice (see figures 12 and 13), particularly during summer. It is during summer that such decreases in sea ice are most crucial because the more reflective sea ice absorbs far less energy from the 24-hour summer sunlight than the darker, more absorptive ocean. Thus the absence of sea ice is an amplifying factor of the initial atmospheric warming, resulting in greater warming in the Arctic than the rest of the planet.

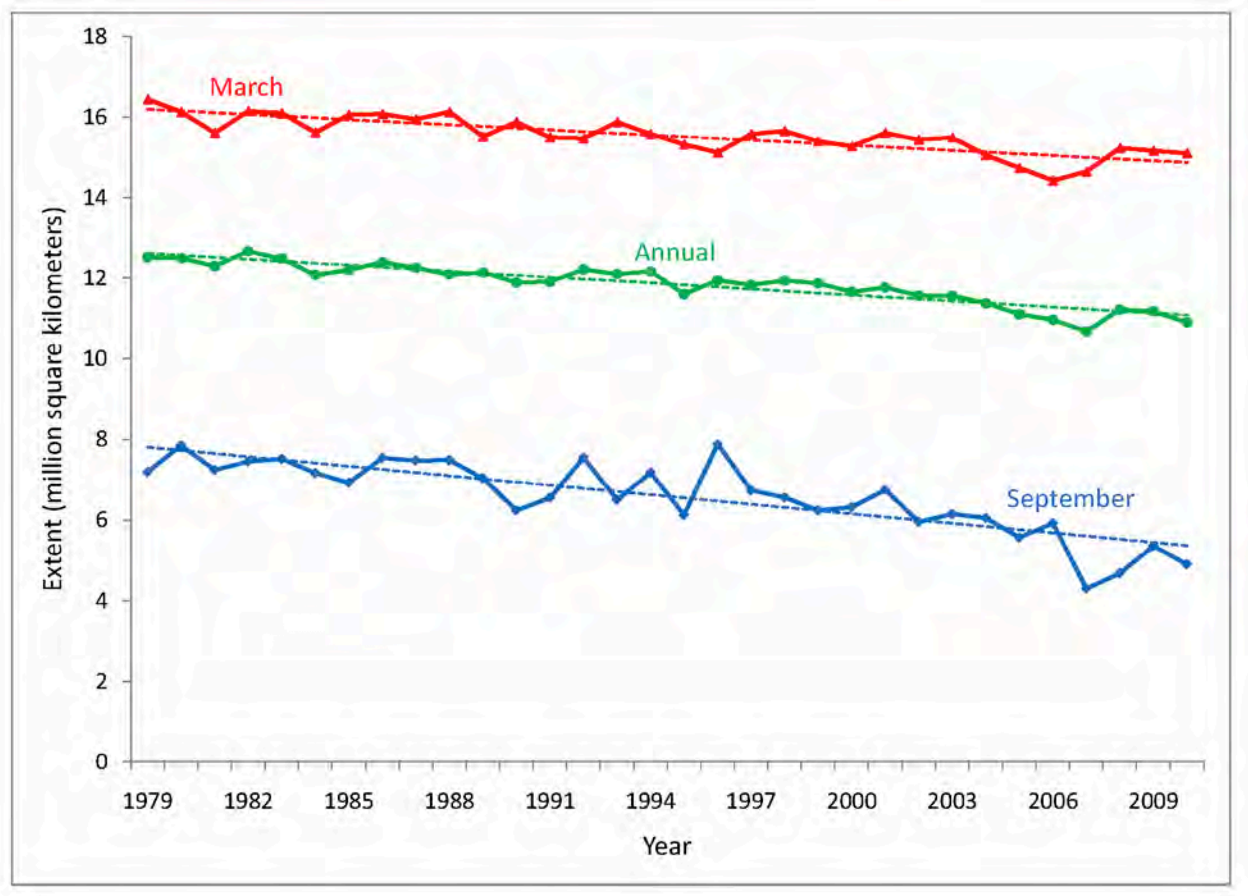


Figure 12. Winter, summer and annual sea ice extent.

Summer Arctic sea ice is declining at the rate of -11.6% per decade. Over the last four years the decline was as follows:

- 2007: 39% below average
- 2008: 34% below average
- 2009: 24% below average
- 2010: 30% below average

If the Arctic becomes sea ice free during the summer, which is possible in 2-3 decades, wind and ocean current circulation patterns will be substantially affected. The large-scale circulations, such as the jet stream, are at least partly due to the difference in heating between the lower latitudes and higher latitudes. Without sea ice, which keeps the Arctic cooler than it normally would be, the Arctic will be warmer and the temperature difference between lower latitudes and higher latitudes will decrease.

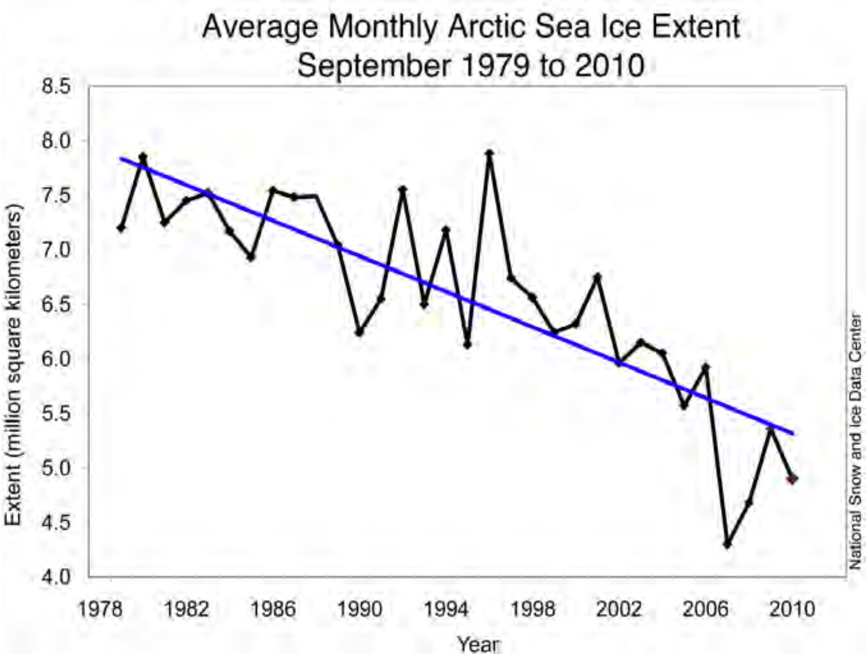


Figure 13. Average September Arctic sea ice extent (1979-2010). Additional details on sea ice loss are shown in figure 21.

As shown in figure 14, sea ice extent observations show a faster decline than forecast by IPCC models (Stroeve et al., 2007). The data also shows that the “summer” season shifting and lengthening.

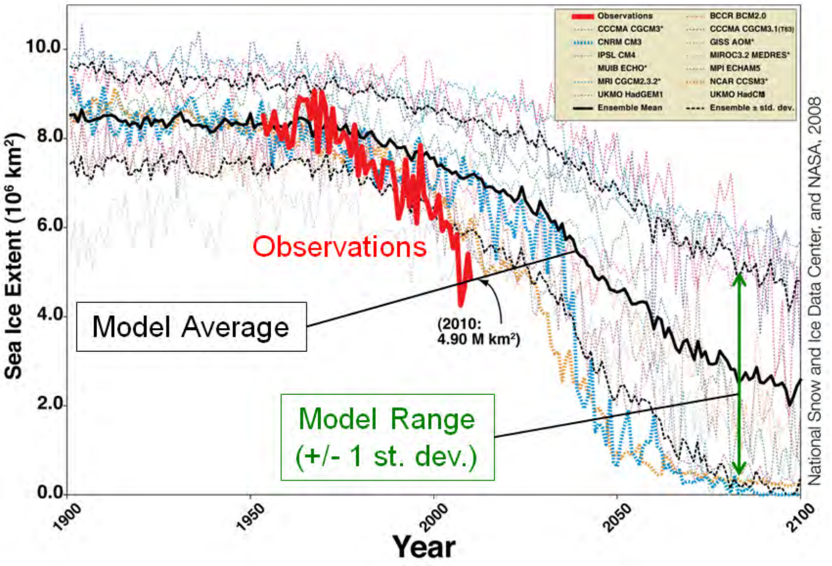


Figure 14. Arctic September average sea ice extent, IPCC AR4 models, 1900-2100, observations, 1953-2010 (Stroeve et al., 2007)

Observations on sea ice thickness are derived from the following sources:

- 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

Observations indicate that ice is getting younger and thinner. As a proxy for ice thickness (all other things being equal), older ice equals thicker ice. Old ice used to cover most of central Arctic. Now it is mostly limited to a narrow band along Greenland and the Canadian Archipelago. Much of the older, thicker ice north of Alaska is melting away during summer.

With respect to ice transport, sea ice moves with winds and currents. Sea ice moves out of the Arctic through Fram Strait, and is replenished by new ice. One way of comparing observed motions is to compare agreement between observed motion and free-drift models using the following equations:

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

Figure 15 shows the change in ice speed ratio and ice-wind direction difference from 1985 through 2009 for first year ice, multi-year ice and all motions.

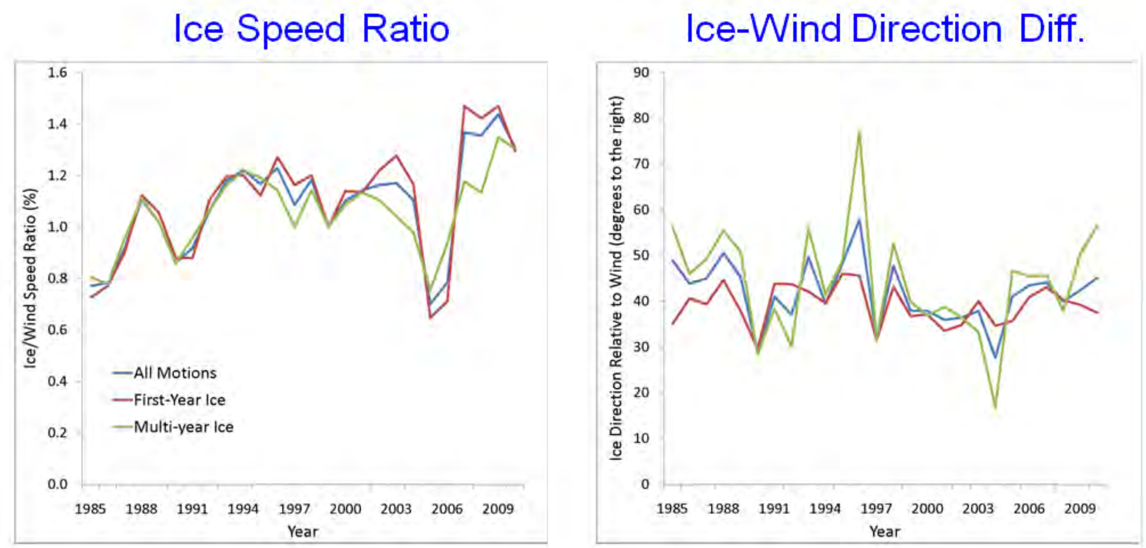


Figure 15. Changes in ice speed ratio and ice-wind direction difference.

3.3 Effects of Climate Change on OSRA Model Inputs

3.3.1 Arctic Basin Hydrography - Dr. Mike Steele

According to Steele et al (2008), “ocean temperature profiles and satellite data have been analyzed for summertime sea surface temperature (SST) and upper ocean heat content variations over the past century, with a focus on the Arctic Ocean peripheral seas. We find that many areas cooled up to ~0.5°C per decade during 1930–1965 as the Arctic Oscillation (AO) index generally fell, while these areas warmed during 1965–1995 as the AO index generally rose. Warming is particularly pronounced since 1995, and especially since 2000. Summer 2007 SST anomalies are up to 5°C (see figure 16). The increase in upper ocean summertime warming since 1965 is sufficient to reduce the following winter's ice growth by as much as 0.75 m. Alternatively, this heat may return to the atmosphere before any ice forms, representing a fall freeze-up delay of two weeks to two months. This returned heat might be carried by winds over terrestrial tundra ecosystems, contributing to the local heat budget”.

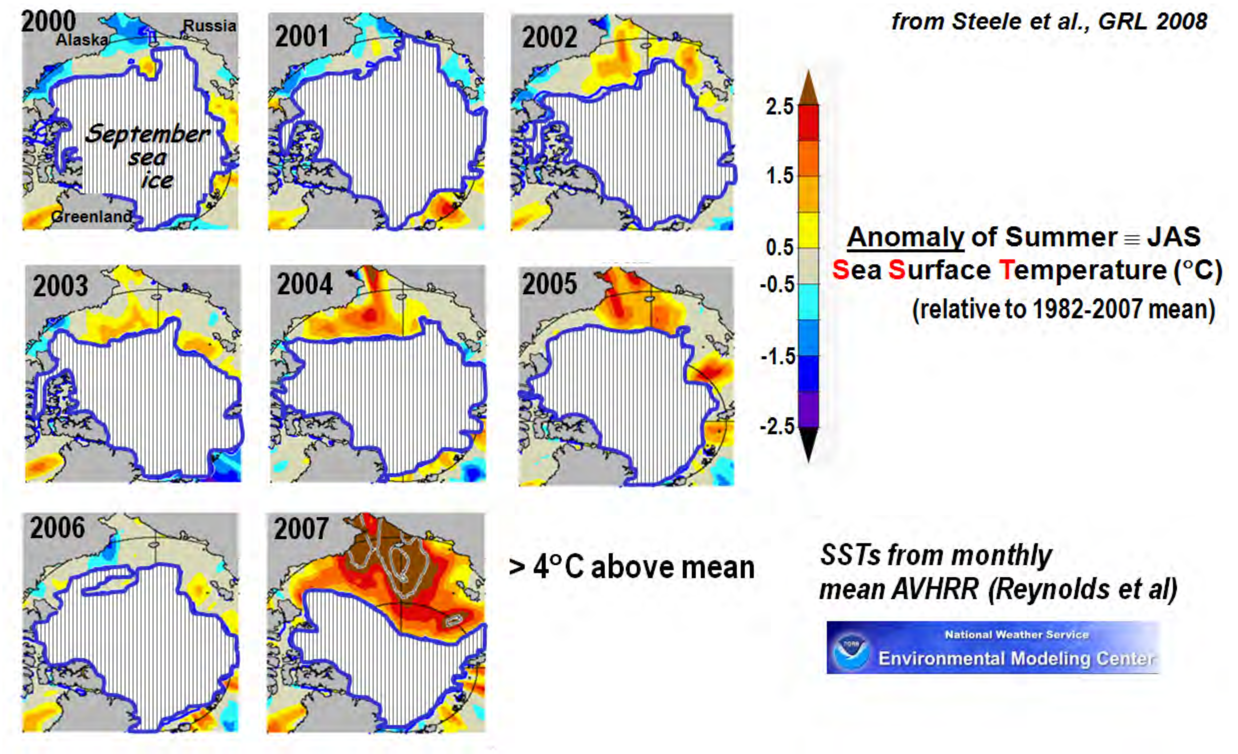


Figure 16. Ice retreat and upper ocean warming.

As reported by Steele et al. (2010), “in this study, we use a numerical sea-ice-ocean model to examine what causes summertime upper ocean warming and sea ice melt during the 21st century in the Arctic Ocean. Our first question is, ‘What causes the ocean to warm in the Pacific Sector during the summer’? We find that about 80% of total heating over this region comes from ocean surface heat flux, with the remaining 20% originating in ocean lateral heat flux convergence. The latter occurs mostly within a few hundred kilometers of the northwest Alaskan coast. In the summer of 2007, the ocean gained just over twice the amount of heat it did over the average of the previous 7 years (see figure 17). Our second question is, ‘What causes sea ice to melt in the Pacific Sector during summer’? Our analysis shows (see figures 18 and 19) that top melt dominates total melt early in the summer, while bottom melt (and in particular, bottom melt due to ocean heat transport) dominates later in the summer as atmospheric heating declines. Bottom melt rates in summer 2007 were 34% higher relative to the previous 7 year average. The modeled partition of top versus bottom melt closely matches observed melt rates obtained by a drifting buoy. Bottom melting contributes about 2/3 of total volume melt but is geographically confined to the Marginal Ice Zone, while top melting contributes a lesser 1/3 of volume melt but occurs over a much broader area of the ice pack.”

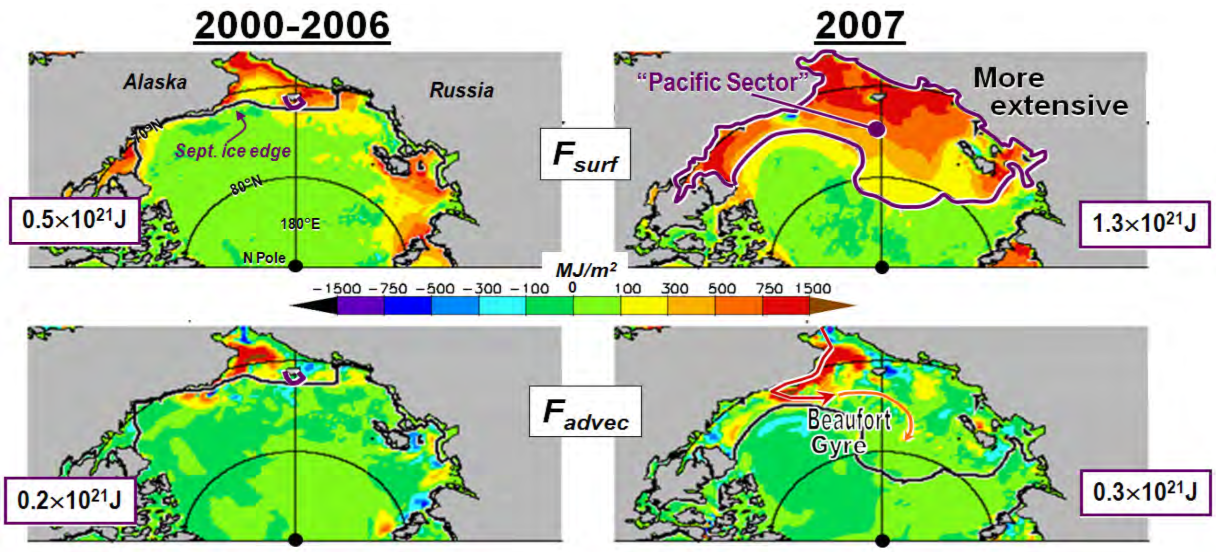


Figure 17. Summer ocean heating in the Arctic (F_{advec} – lateral heat flux convergence, Fsurf = net air ocean heat flux, ice penetrating solar heat flux and ice-ocean heat flux).

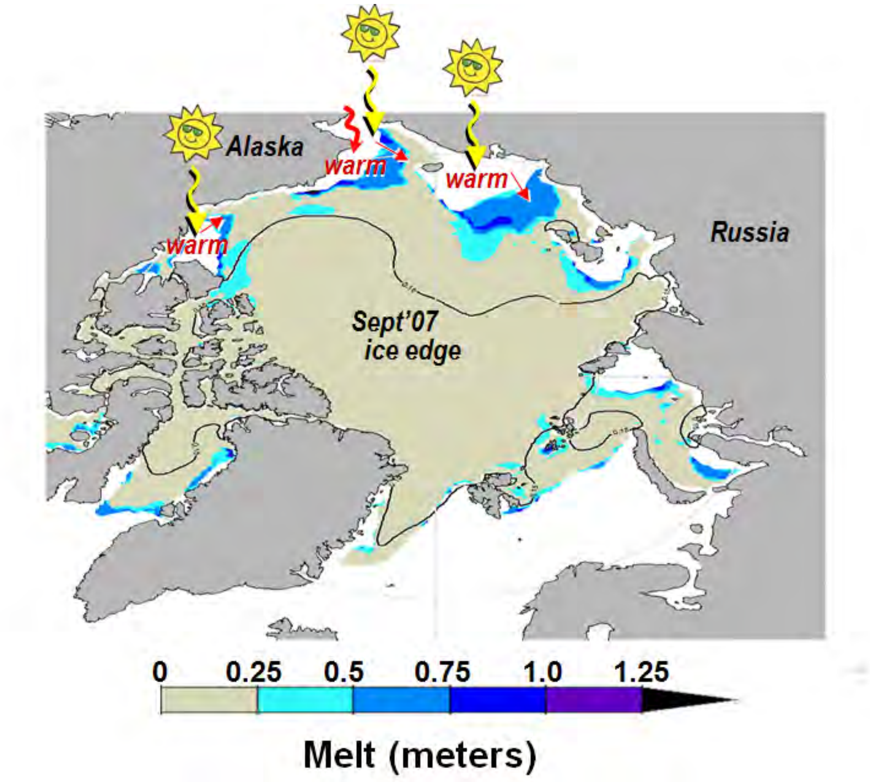


Figure 18. Map showing the September 2007 ice edge.

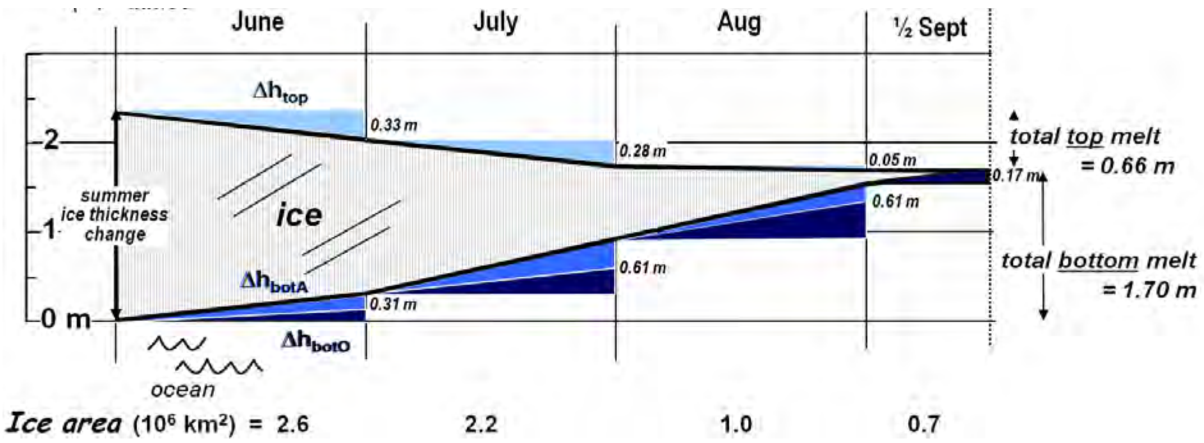


Figure 19. Ice thickness budget for 2007.

The formation of a Near-Surface Temperature Maximum (NSTM is a local, seasonal feature caused by penetrative short wave solar heating (see figure 20). The NSTM first formed in June-July when sufficient solar radiation enters the upper ocean through narrow leads and melt ponds to warm the near-surface waters. The NSTM contains enough heat to melt up to 1 m of sea ice.

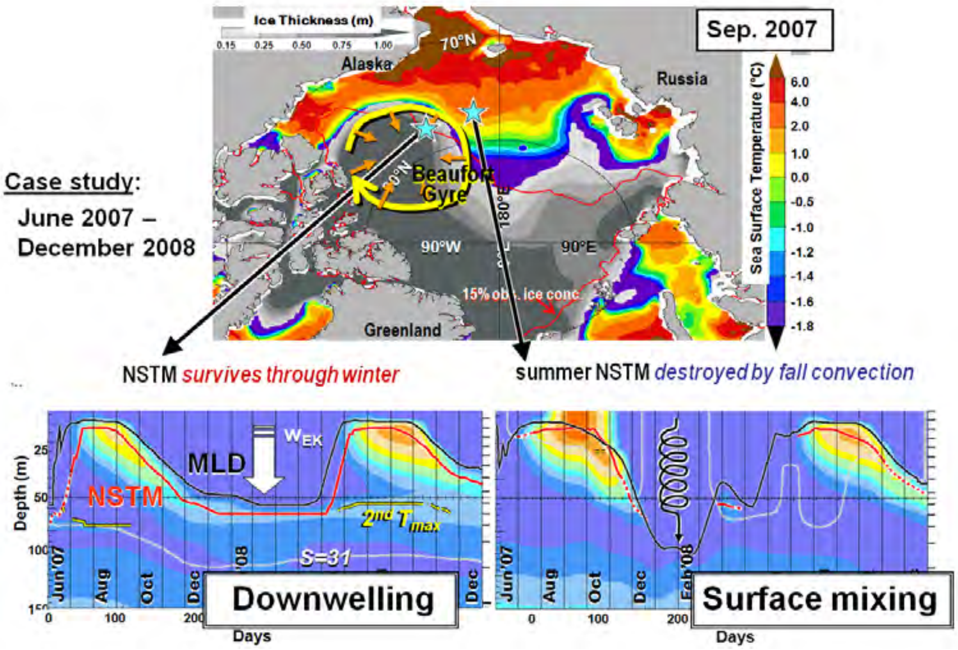


Figure 20. Formation of the NSTM in the Arctic.

Three factors are responsible for the recent winter survival of the NSTM:

- Thinner, looser ice cover allow more summer heating
- Increasing Beaufort Gyre stratification suppresses surface mixing

- Increasing Beaufort Gyre causes downwelling

In summary, the major factors influencing Arctic Ocean circulation are:

- sea ice thinning and retreat
    - vertical momentum flux changes (currents, waves, mixing)
    - surface warming (ice melt, tracer, density)
    - vertical freshwater (FW) flux changes? (density)
- changes in the global hydrologic cycle
    - increasing FW input (density)
    - altered Pacific-Atlantic ΔSSH?

New developments in Arctic Ocean circulation modeling include:

- numerical improvements (e.g., resolution)
- better forcing (e.g., atmospheric re-analyses)
- new tracers and diagnostics (e.g., biology!)

3.3.2 The Changing Arctic: Observation and Model Study - Dr. Muyin Wang

Changing conditions in the Arctic are demonstrated by annual temperature increases, the melting of ice on Greenland and the diminishing extent of sea ice in the Arctic. The latter is shown in figure 21 as a downward trend of some 6.7%/decade over the past three decades. This decrease in the extent of Arctic sea ice has been observed throughout the northern hemisphere, and there has been a reduction in multiyear ice as well.

The Arctic system may be displaying a positive feedback to the observed perturbation. The elements in this environmental behavior are displayed in figure 22 where the warmed atmosphere leads to a reduction in ice cover and ice thickness followed by a reduced albedo and the further warming of the atmosphere. Presumably there also would be increases in the flux of moisture from the ice free ocean to the atmosphere and consequent changes in precipitation. The annual sea surface temperature anomaly, based upon the 1982-2007 mean illustrates the dynamic nature of change in the Arctic. The dramatic increase in sea surface temperature anomaly observed in 2007 is followed by equally dramatic decreases during 2008 and 2009. The Arctic Oscillation is important to understanding these changes. Readers are referred to the full presentation for illustrations of Oscillation over the past three decades along with a schematic of associated weather patterns.

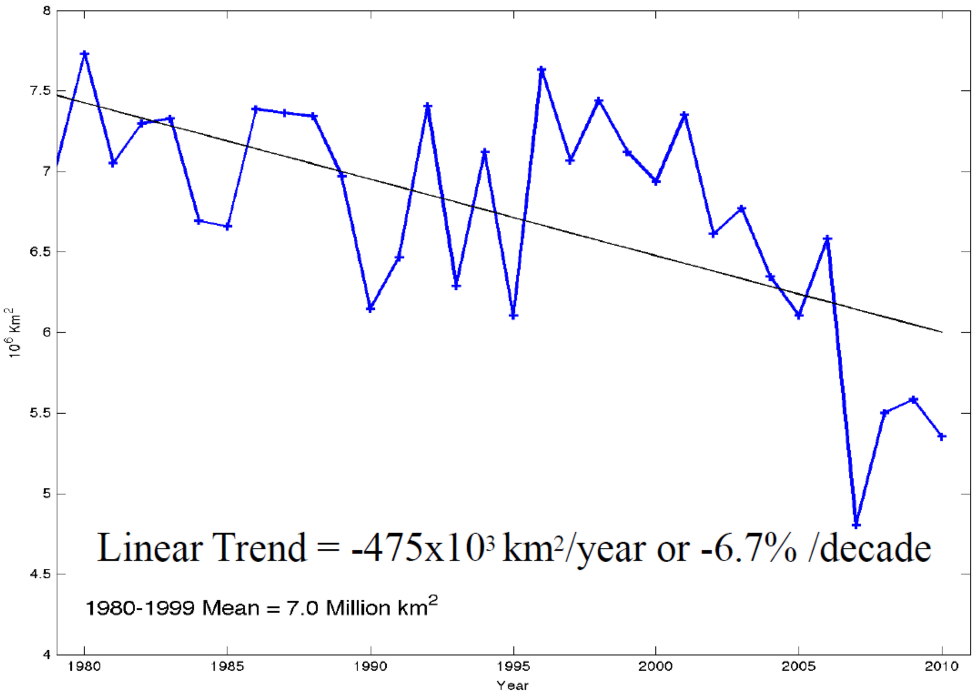


Figure 21. Trend in Arctic September sea ice extent.

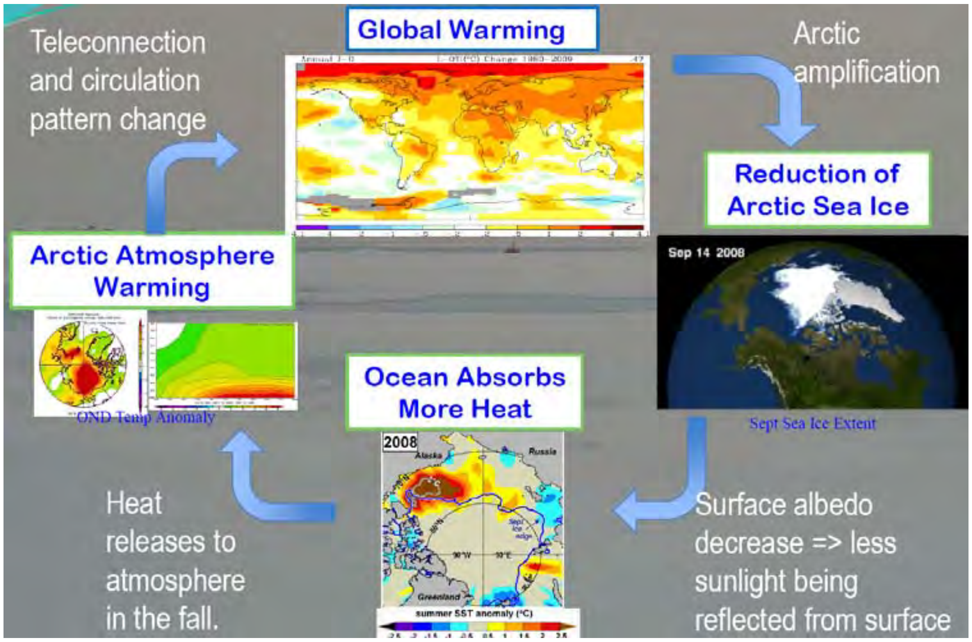
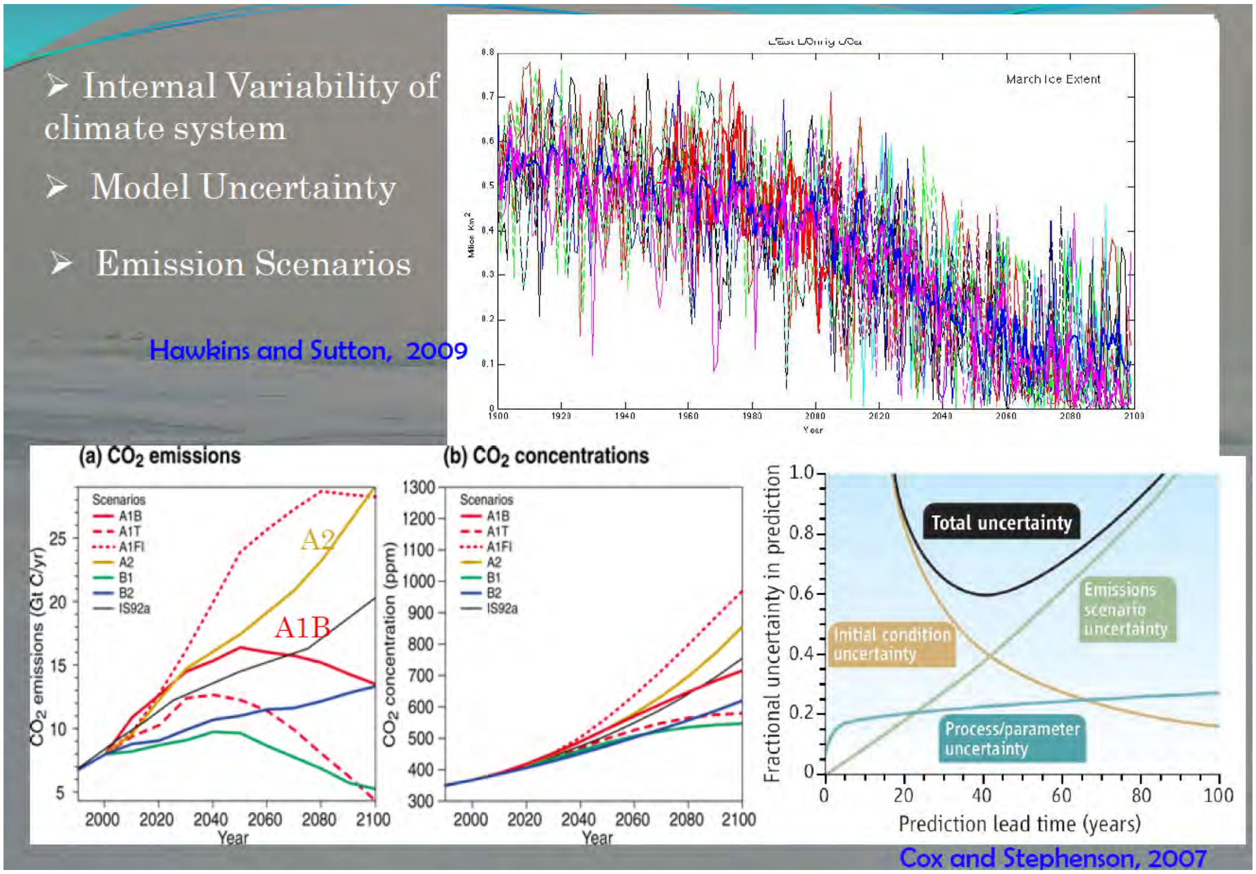


Figure 22. Arctic climate system feedbacks.

There are numerous ways to model the Arctic in attempts to capture the observed behaviors of the atmosphere, ice and ocean and thus an amount of model culling is necessary. Climate models as recently as 15 years ago were quite coarse in their vertical and horizontal resolutions and lacking many processes in comparison with today's models. Uncertainties in climate model projections result from internal variations in the climate system, model uncertainties and variation in carbon dioxide emission scenarios. The summation of uncertainties versus projection time shown in figure 23 provides a quantitative estimation of the possible consequences of using forecast model outputs within the OSRA process and subsequent environmental impact analyses conducted by BOEMRE.



- Internal Variability of climate system
- Model Uncertainty
- Emission Scenarios

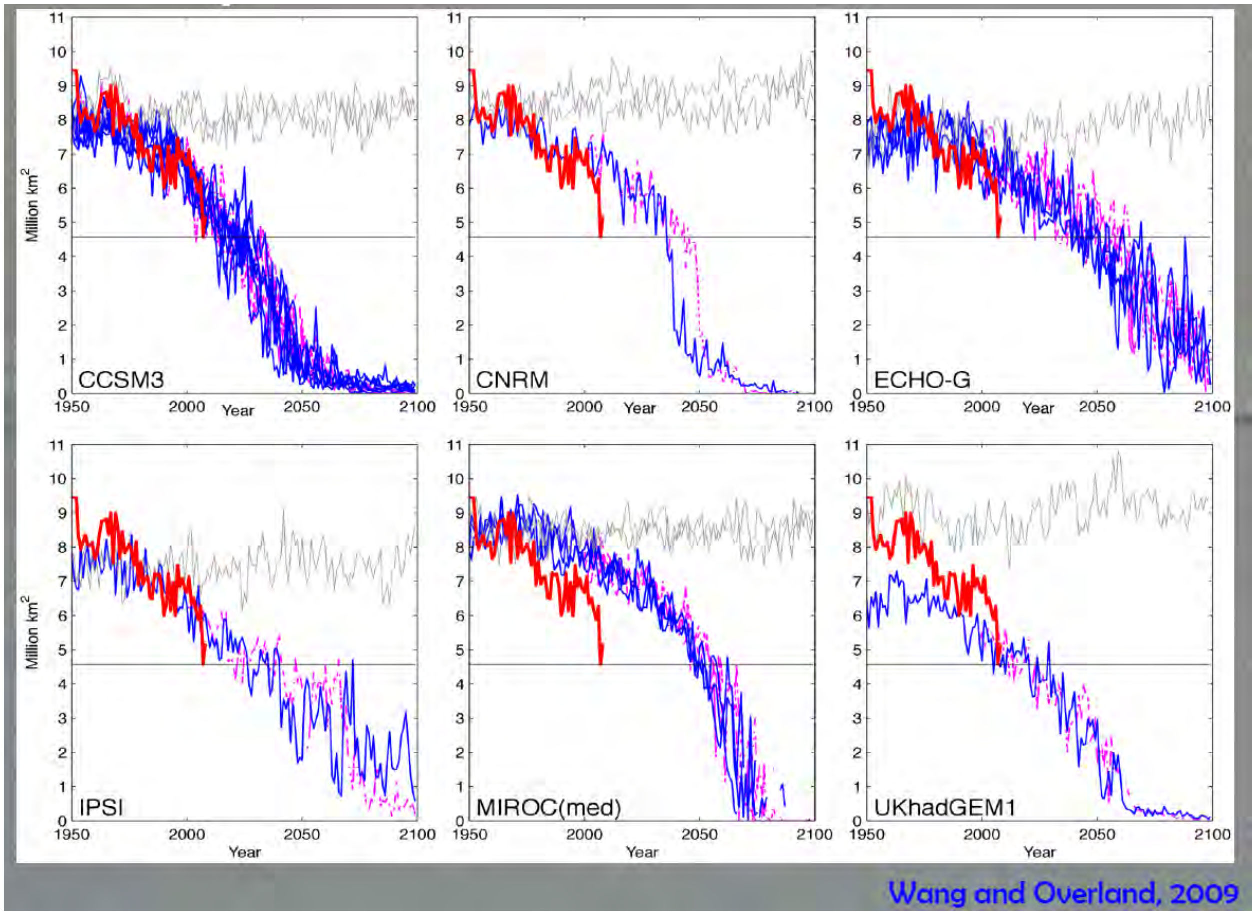
Hawkins and Sutton, 2009

Cox and Stephenson, 2007

Figure 23. Source of projection uncertainties.

Example model projections and their variations can be seen in figure 24 showing the extent of sea ice in the northern hemisphere during the month of September over one and one half centuries. A half century of observations have been included in the illustration.

An ice free Arctic has been projected for summer, 2037 using the extent of sea ice cover observed in 2007 and 2008, as reported in Wang and Overland (2009).



Wang and Overland, 2009

Figure 24. Modeled projections of sea ice extent.

3.3.3 Toward producing reanalysis wind field over the Chukchi/Beaufort Seas via data assimilation and analysis nudging - Dr. Jing Zhang

For long-term simulations there is a need to improve model performance through increased accuracy and constraining model solutions to prevent large error growth; these are accomplished through data assimilation and analysis nudging, respectively. An example case concerns the modeling of surface (10m) winds over the Beaufort and Chukchi Seas. Observations from the NASA/JPL SeaWinds scatterometer, QuikSCAT for the period 1999-2009 were used (assimilated), to produce the winds shown in figure 25.

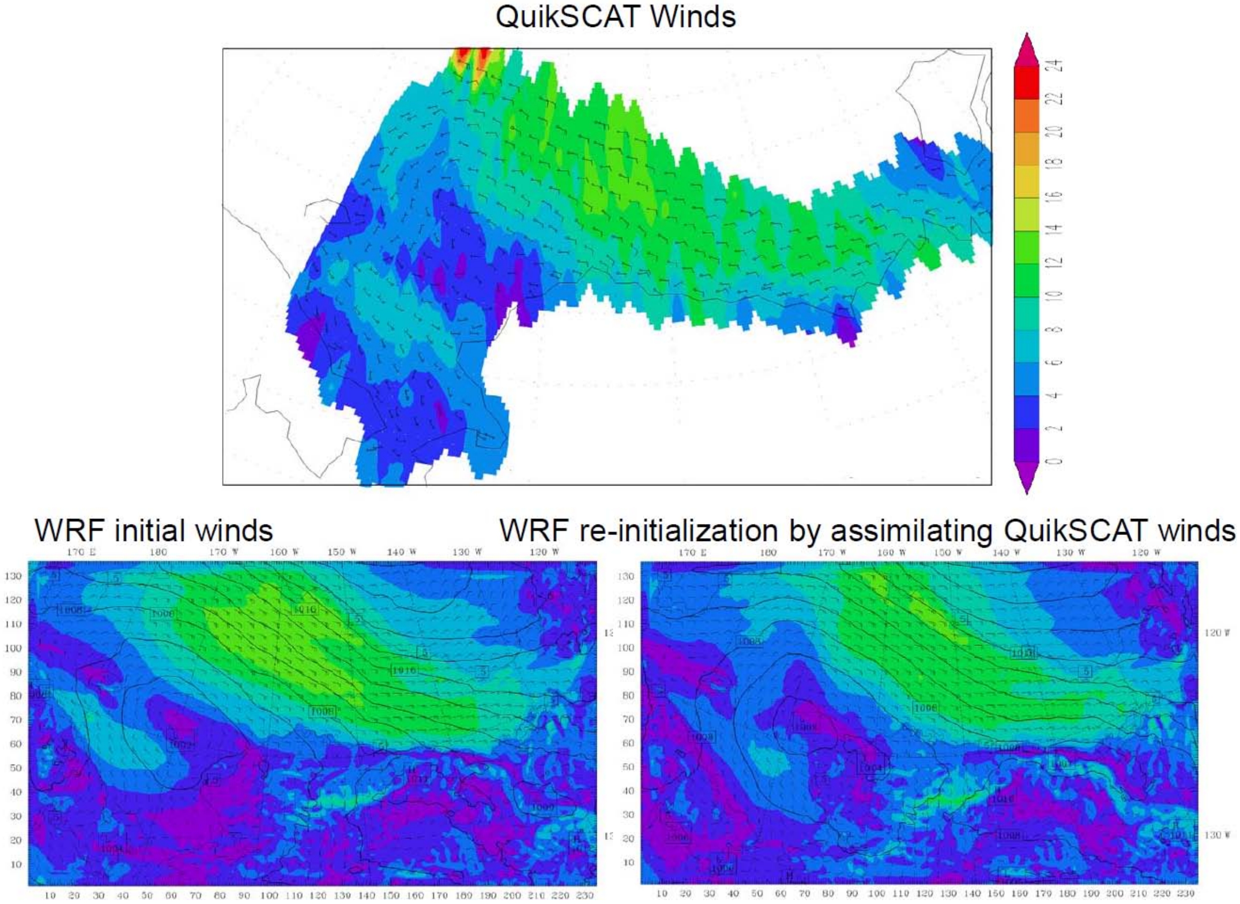
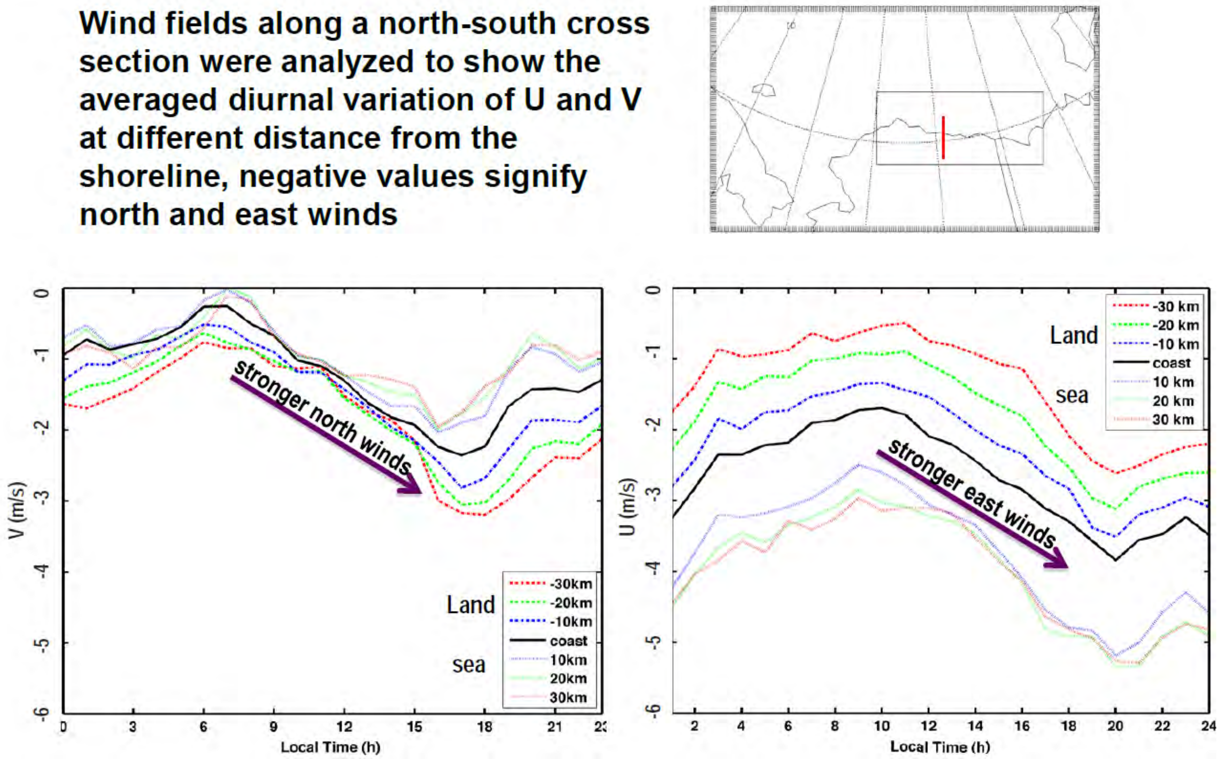


Figure 25. Assimilating QuikSCAT winds into the Weather Research and Forecasting (WRF) model.

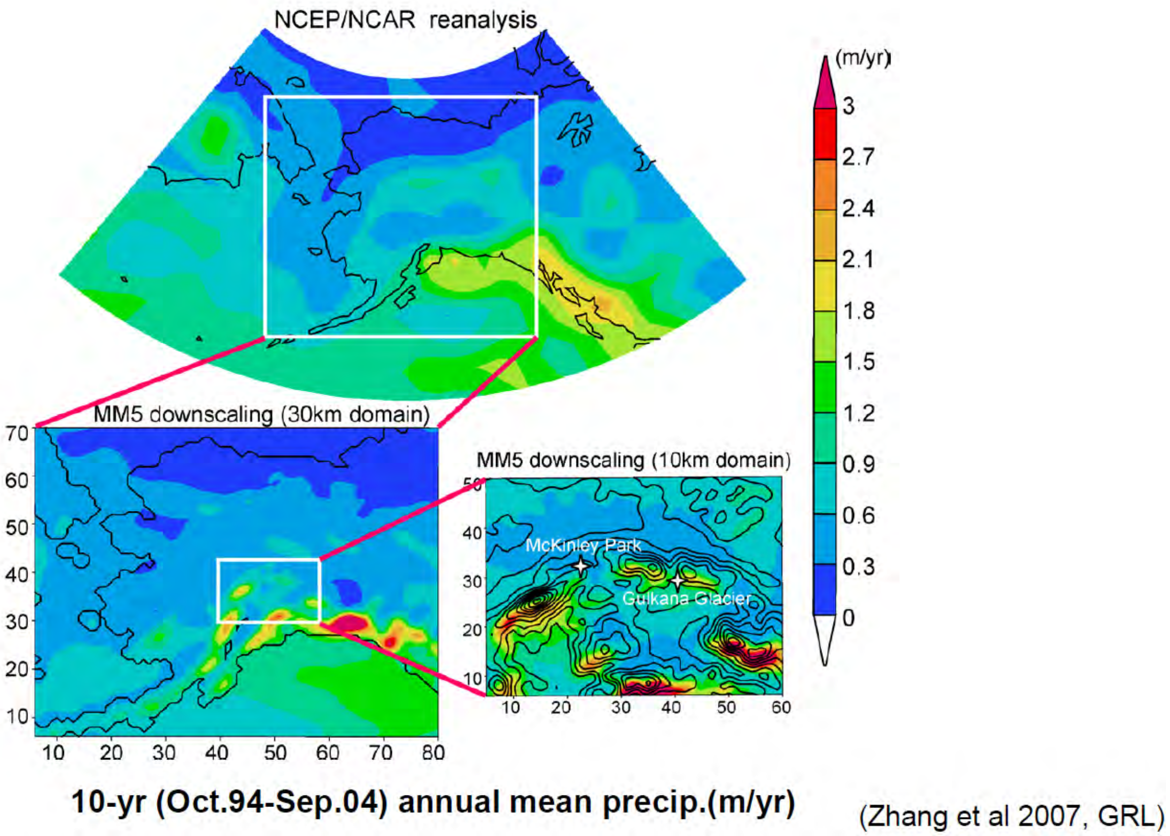
Additional observations from radiosondes, surface stations and MODIS and COSMIC profiles were then included in the Weather Research and Forecasting (WRF) model, along with the 3-D analysis spectral nudging option. The resulting averaged diurnal variations in U and V components of velocity along a land-sea cross section are shown in figure 26.



Wind fields along a north-south cross section were analyzed to show the averaged diurnal variation of U and V at different distance from the shoreline, negative values signify north and east winds

Figure 26. Mean diurnal variation of V and U.

The sea and land breezes are especially important for their effects on nearshore spills. And, the coastal and nearshore regions experience extreme wind events (10 – 20 m/s or greater) during Arctic summer (Sept. /Oct.) when the sea ice extent is minimal. Downscaling from the GCM has been shown, for example, in the case of precipitation (see figure 27) to yield excellent results.



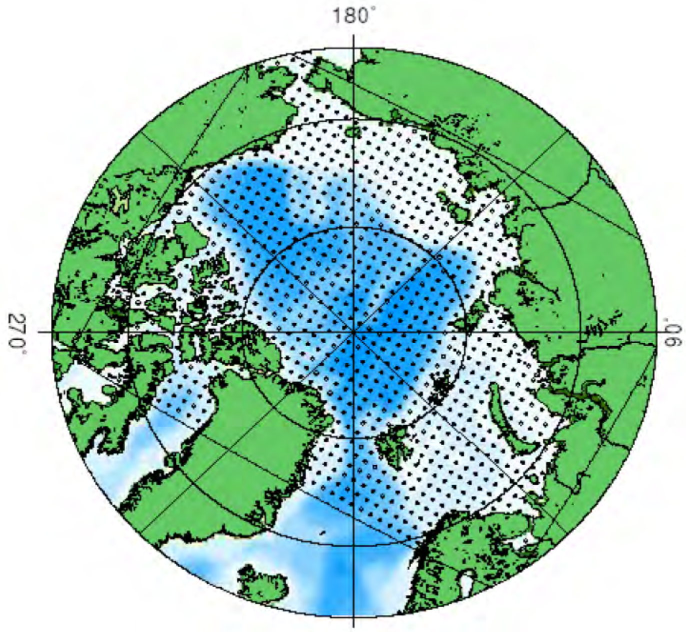
(Zhang et al 2007, GRL)

Figure 27. Example of downscaling precipitation.

3.4 Comparison of Hindcast/Forecast Model Results

3.4.1 Arctic Ocean Model Intercomparison Project and Model Strengths and Weaknesses – Dr. Andrey Proshutinsky

The Arctic Ocean Model Intercomparison Project (AOMIP) is an international effort to identify systematic errors in models and reduce uncertainties in model results and climate prediction. In addition to identifying the models (both global and regional) and the professionals involved with AOMIP, the accompanying appendix includes the following detail for each model: vertical grid coordinates, nodes, domains, treatment of friction, time step, equation of state, mixing, advection, sea ice dynamics and thermodynamics, atmosphere-ocean exchange, ocean-sea ice exchange and radiation. The models make use of standardized forcing data sets for: bathymetry, river runoff, sea ice, hydrography, derived reanalysis products for atmospheric forcing, surface-restoring forcing data, and a common modeling domain (see figure 28).



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.

Figure 28. AOMIP common modeling domain.

Attempts have been made to validate the atmospheric forcing data, for example, by comparing the NCEP/NCAR reanalysis data with observations from the Russian North Pole Stations. Agreement between reanalysis data and observations is good only during winter (see figure 29). Thirty year simulations of sea ice thickness yield a large range of variation (see figure 30).

The failure to form the ‘cold halocline’ suggests that there are missing or misrepresented physics in the AOMIP models. Vertical mixing, if overly strong, weakens the stratification and leads to anticyclonic circulation at all depths. Weak vertical mixing on the other hand overly stratifies leading to a very strong anticyclonic circulation in the upper layer.

Most of the AOMIP models underestimate the thickness of thick ice (>2m) and overestimate the thickness of thin ice (<2m). All of the models exhibit more variability in ice concentration than is found in observations and most underestimate ice concentration it the central Arctic basin in

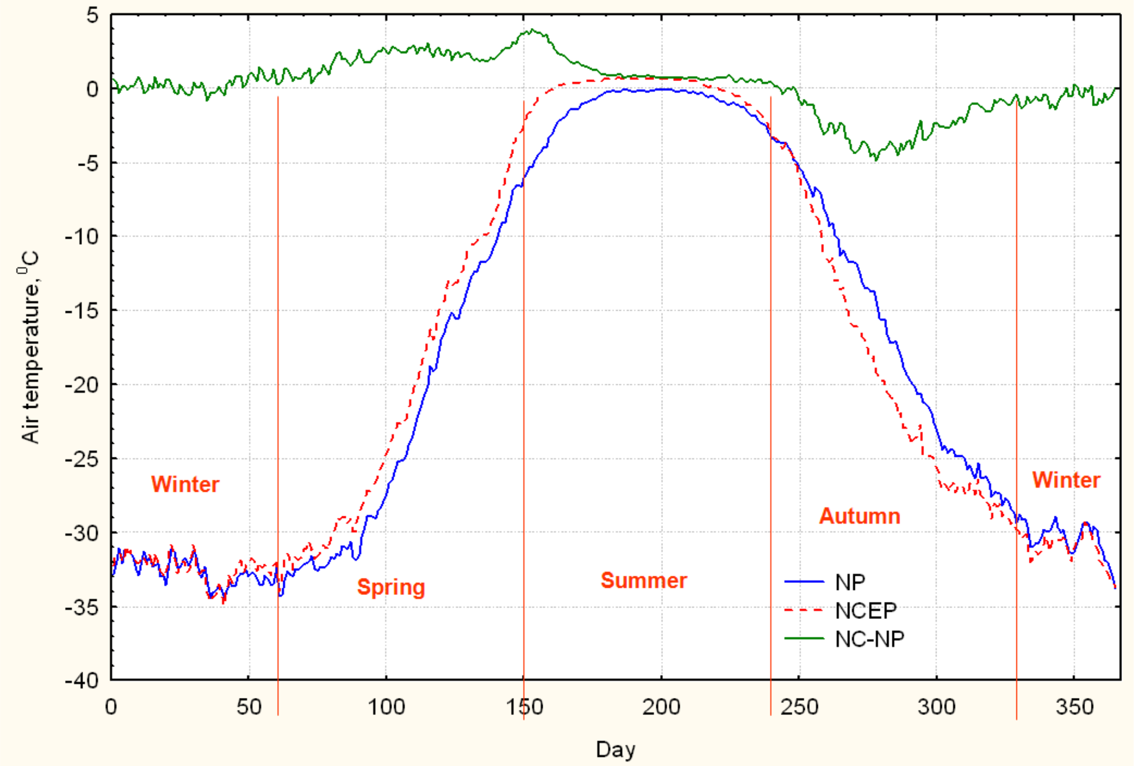
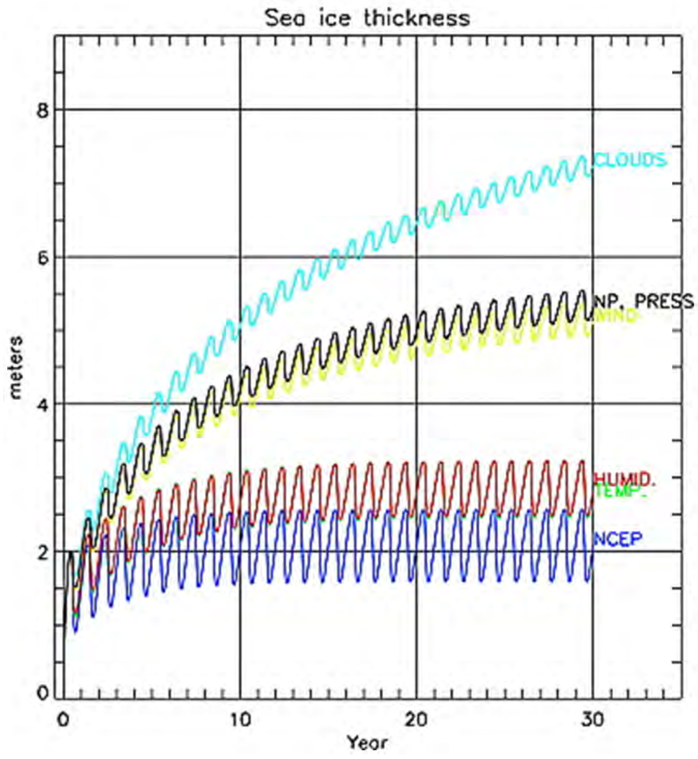


Figure 29. Seasonal variability of air temperature.

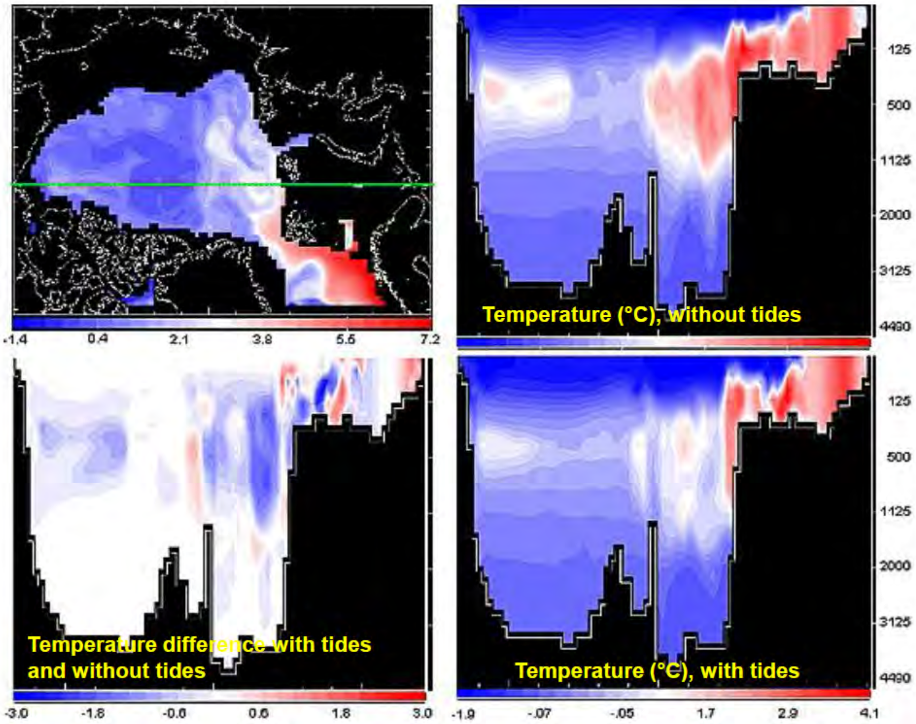


30-year time series of simulated sea ice thickness. Lines depict thickness variability under NCEP and under NP forcing only (NP), under NP forcing using NCEP wind (WIND), NP forcing using NCEP SAT (TEMP.), NP forcing using NCEP specific humidity (HUMID.), and NP forcing using NCEP clouds (CLOUDS).

Figure 30. Variability of sea ice thickness.

September. The ice models exhibit considerable variability in there ice drift, export, deformation, deformation-related ice production and spatial deformation patterns. The model skills for explaining regional ice divergence are poor.

Ocean tides enhance the loss of heat from Atlantic waters (see figure 31). Ice thinning due to this enhanced heat flux competes with net ice growth during opening and closing of tidal leads. Throughout the Intercomparison period (1950 to 2000) models accumulate excessive heat contrary to observations. Tidally induced ventilation of ocean heat reduces this discrepancy.



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

Figure 31. Tidal influence on heat loss.

An effort to improve Arctic tidal modeling is a current focus of AOMIP. Collaborative efforts which address reanalysis of Arctic climate are also underway. The approach uses two models (see figure 32); one, which makes use of a conventional 4-D variational technique, obtains information from a second, which is a regional coupled ice-ocean model.

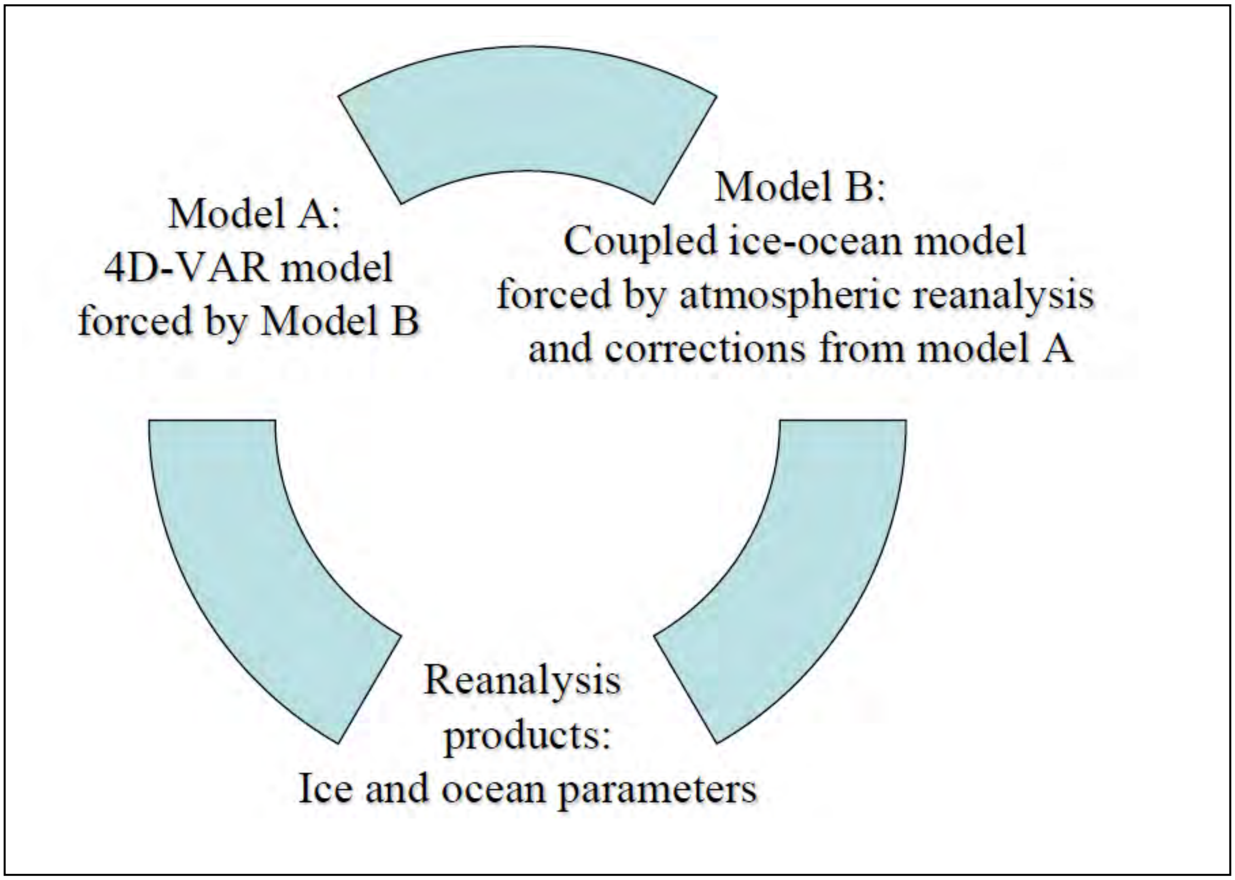


Figure 32. Modeling approach for coupled ice-ocean systems.

Model improvements beyond increased model resolutions will require increasing the quantity and quality of observations and improving data assimilation methods. Better descriptions of small scale processes and deformations are needed, as well as the inclusion of forcing at inertial and tidal frequencies. Other areas in need of model improvement are land fast ice, which is important in the regulation of dynamics and thermodynamics, variable river runoff and the inverse barometer effect. Nearly a dozen coordinated observational and modeling studies are being inaugurated in an attempt to address these deficiencies.

3.4.2 Requirements of Arctic Ocean Hindcast and Forecast Models - Dr. Wieslaw Maslowski

A collaborative effort among several investigators and institutions has been undertaken to examine model capabilities and requirements for improving both hindcast and forecast models. The result of these efforts over the past four years has been the development of the Regional Arctic Climate system Model (RACM). RACM is considered by some to be the best tool for regional synoptic and climate prediction. The RACM domains for coupling and topography are illustrated in figure 33.

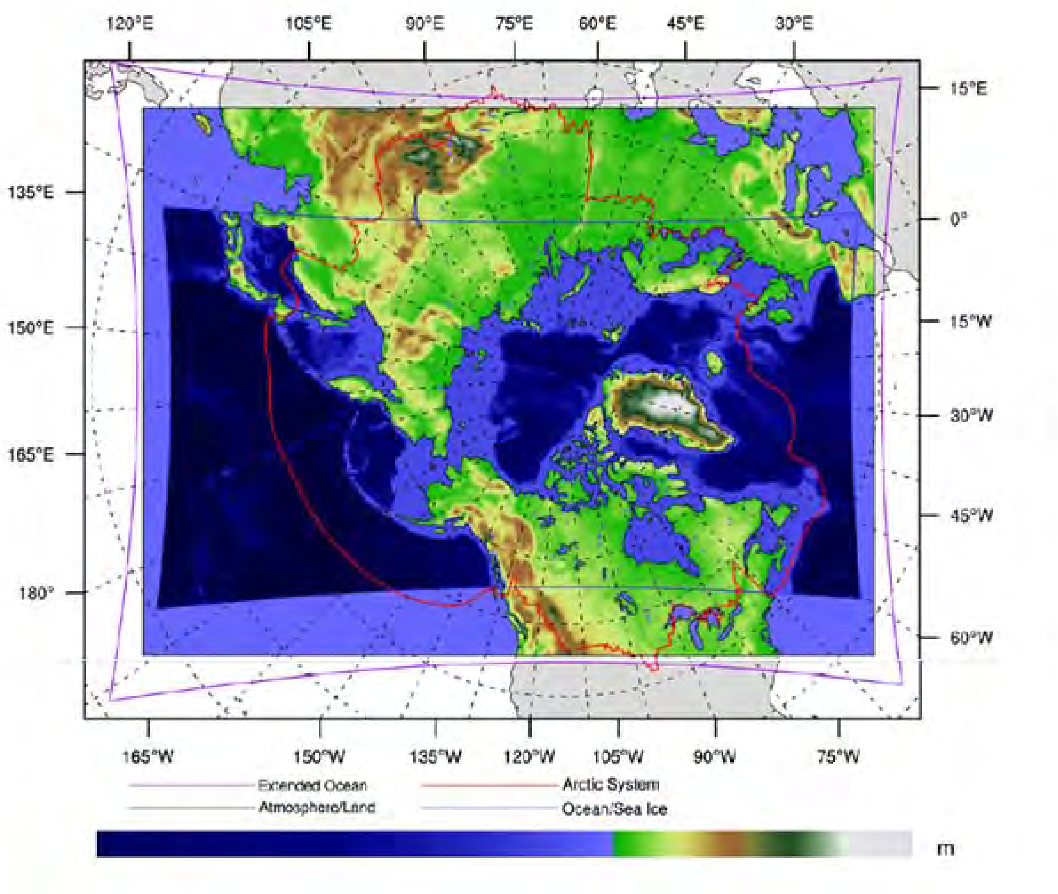


Figure 33. RACM domains for coupling and topography.

The total sea ice coverage of the Northern Hemisphere is included as well as all river drainage to the Arctic basin. Large scale atmospheric patterns and inter-ocean exchange and transport are enabled. The WRF and the Variable Infiltration Capacity (VIC) model domains include the entire colored region. Parallel Ocean Program (POP) and Los Alamos Sea Ice Model (CICE) domains are bounded by the inner blue rectangle. Shading indicates model topobathymetry. The

Arctic system domain (red line) is defined in Roberts et al. (2010). The development of RACM addressed the following (Roberts et al., 2010):

- 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

Included in the rationale for developing RACM was the need for regional assessment and policy making within the region. Example output from RACM showing a comparison of summer/winter sea ice concentrations is presented in figure 34, and sea ice deformations are illustrated in figure 35. Fully coupled high-resolution regional climate models are improving and, equally important, they allow examination of incorporating enhanced observations and computational resolutions.

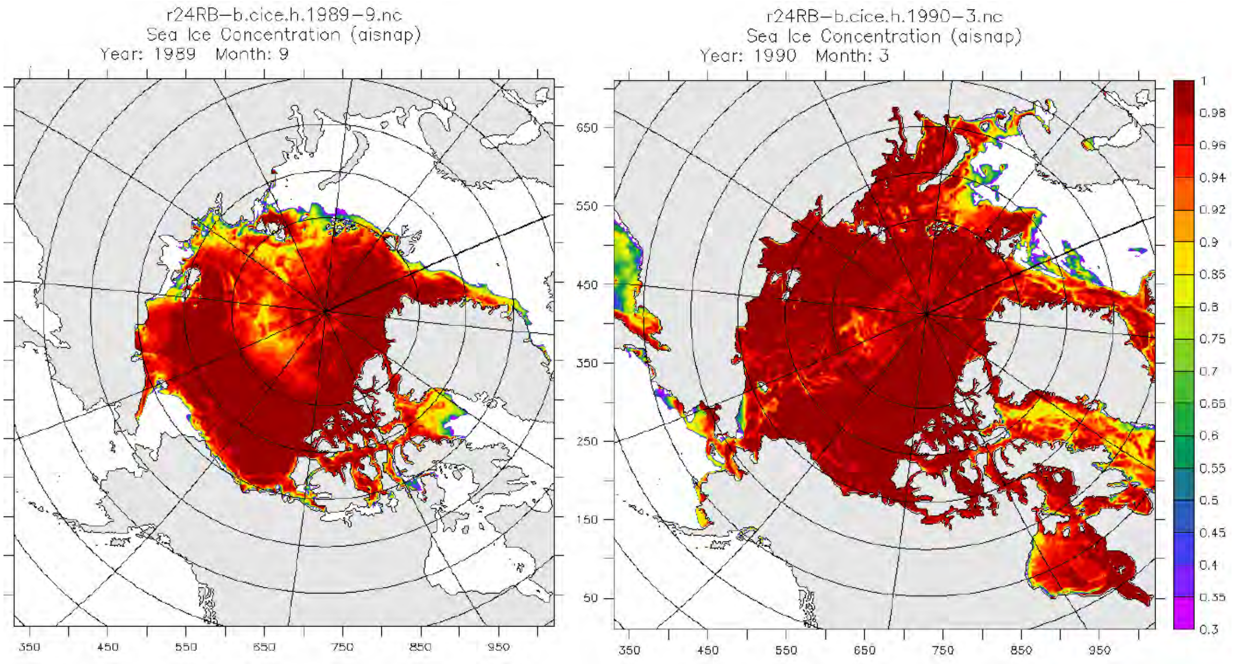


Figure 34. Summer (left) and winter (right) RACM sea ice concentrations

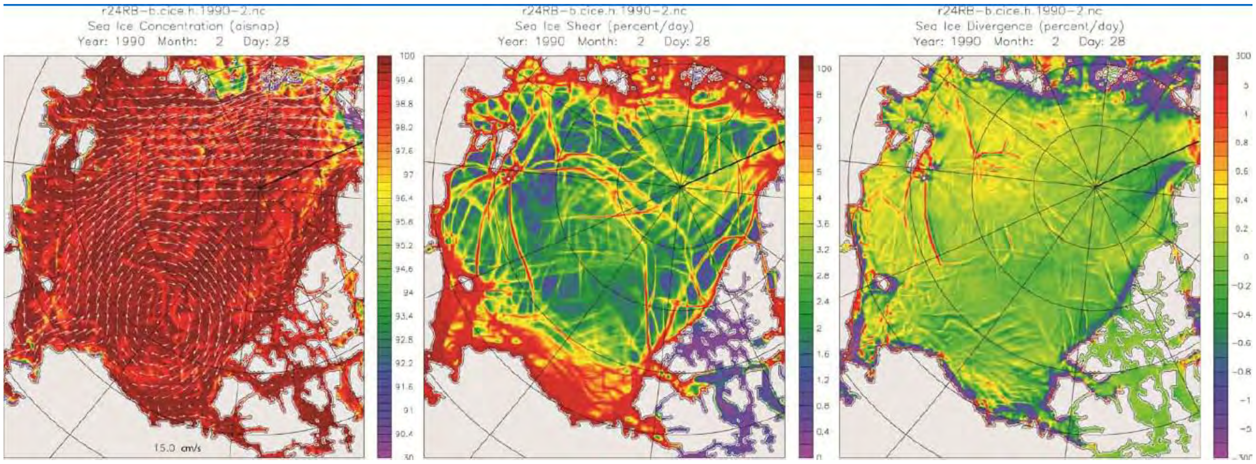


Figure 35. Fully coupled RACM sea ice deformations.

3.4.3 Assessing skill of Arctic ocean – ice models - Dr. Greg Holloway

How might various models be compared and their relative skills determined? Simple parameters, like temperature and salinity can be averaged and compared with ease, in contrast with vectors such as velocity. A scalar named topostrophy is produced from the dot product of the gradient of total depth with the cross product of the Coriolis and velocity vectors (Holloway, 2008).

Among nine Arctic models the topostrophy of three is quite distinct from the other six (see figure 36). This distinction among models has been shown to be dependent upon the subgrid scale eddy parameterization. Improved numerical representations within models result in larger values of topostrophy. The topostrophy parameter has been calculated from the worldwide distribution of current meter records. The distribution of topostrophy, normalized to the range of ±1.0 is shown plotted against latitude in figure 37. The parameter clearly increases in latitude and has been shown separately to increase with depth.

Two models “ECCO2” at NASA/JPL and “ORCAI” at BIO were used in the following fashion to examine changes in model skill and differences in topostrophy (which is not a measure of model skill). The ECCO2 model was run using grids of: 18km, 9km and 4km. The ORCAI model was

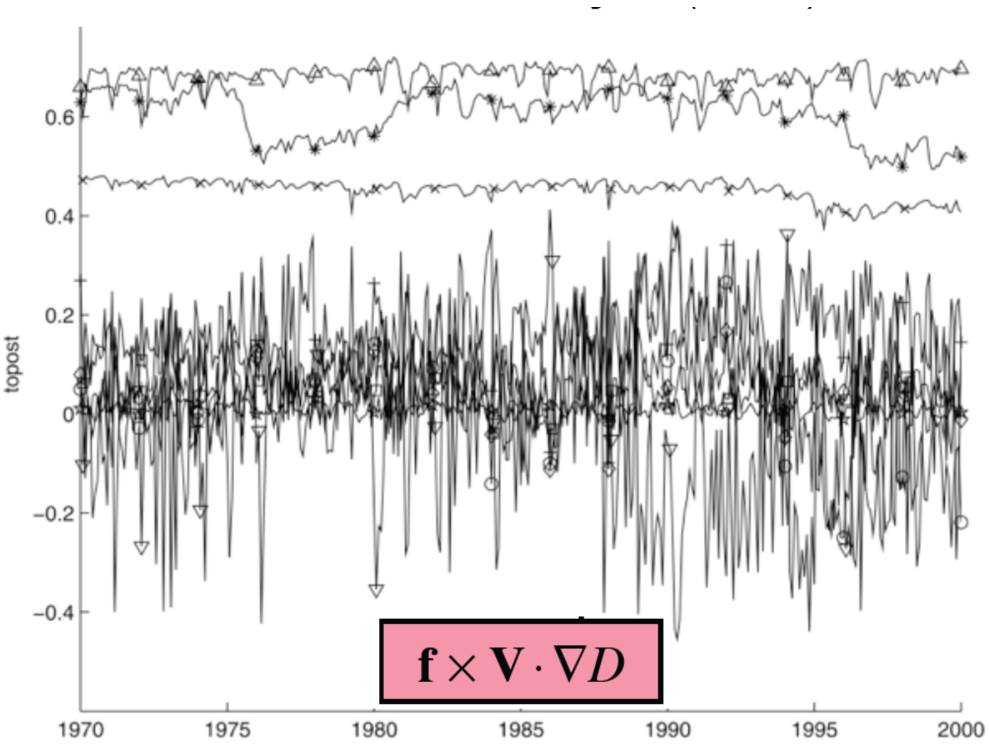


Figure 36. Volume averaged tropstrophy from nine models

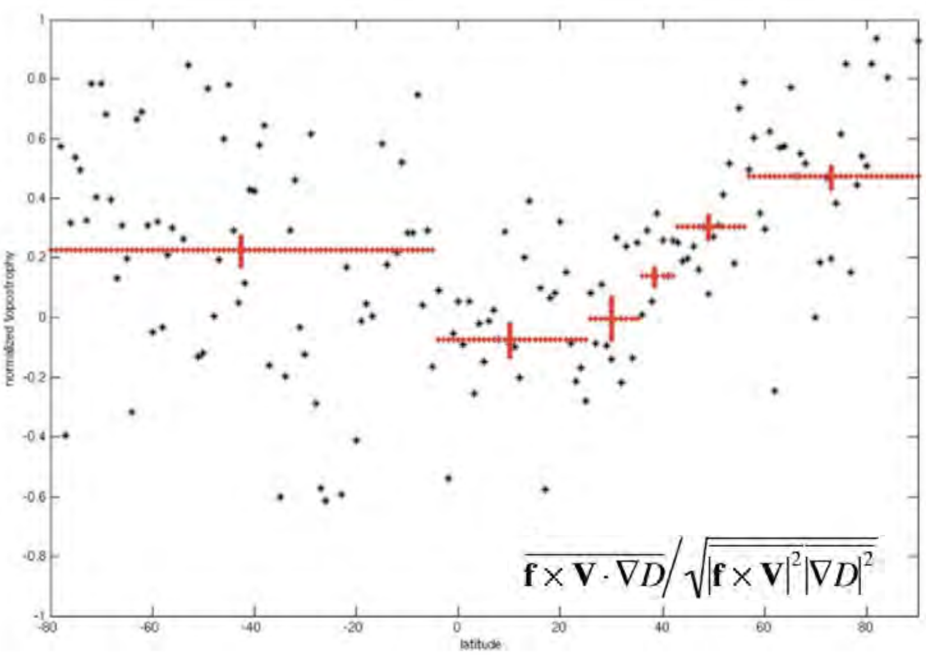
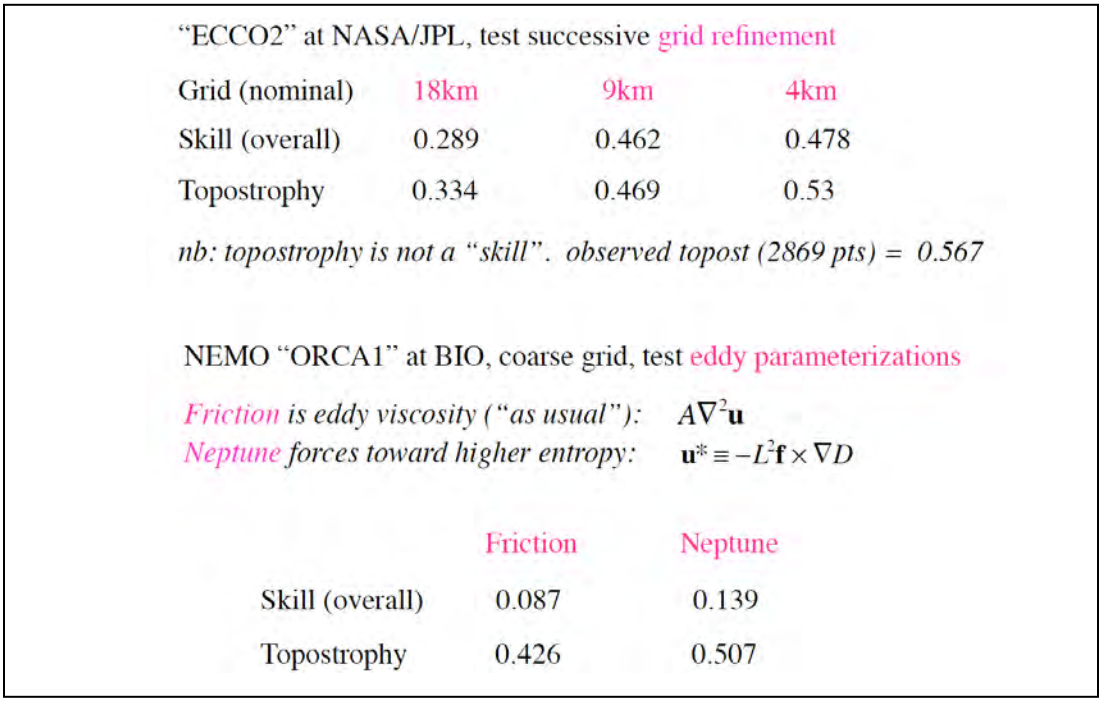


Figure 37. Normalized topostrophy from current meters.

run using two different parameterizations of internal friction. The results of the model studies shown in figure 38 clearly support the use of finer grid resolution and the Neptune scheme for representing friction.



"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

Figure 38. Normalized topostrophy from current meters.

An examination of temperature and salinity was also undertaken. The procedure was to complete a volumetric census of T-S space, dividing the Arctic basin into eight subdomains to account for their regional variation. The test models were run with ECCO2 at 18km and again at 9km, while ORCA2 was run using eddy viscosity and separately using Neptune. The resulting distributions of T-S volumes are shown in figure 39. The T-S volume analysis shown in figure 39 applies to the subdomain labeled "CB" which contains the Beaufort Sea and its extension northward to the pole. Increasing volumes are illustrated with colors of increasing wavelengths. A quantitative measure of skill for the T-S volume studies shows a remarkable similarity between the 18km and 9km model runs, and for the two different eddy parameterizations. The conclusions are that models with finer resolution give improved results and a 4km grid may be adequate. Coarser model grids yield significantly better results with improved eddy parameterization, suggesting the possibilities of tradeoffs between resolution and eddy parameterization.

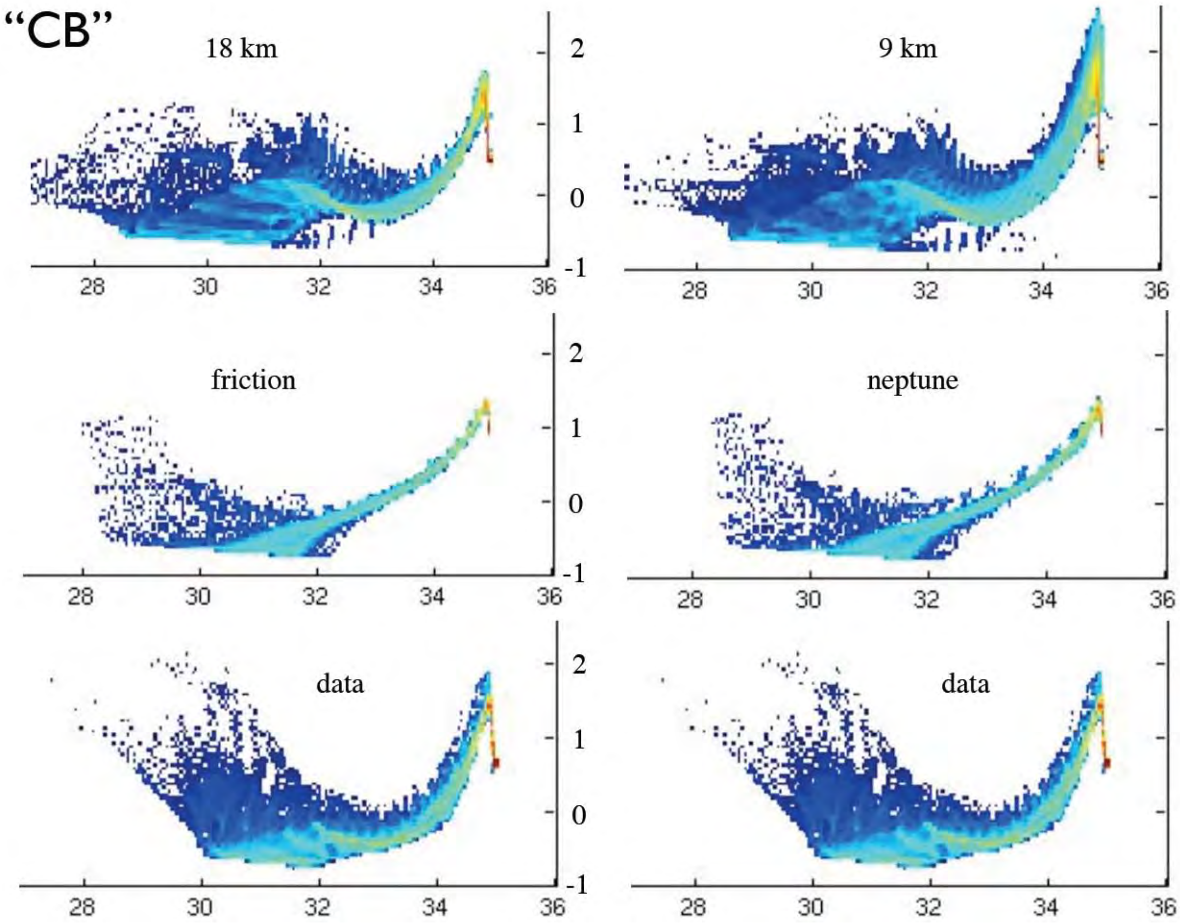


Figure 39. T-S volume analysis.

4. Summary and Recommendations

The OSRA consists of simulating the paths of hypothetical oil spills and is based on hindcasts of the best available ocean currents, winds and ice in the Arctic. During the three day workshop, participants and the Scientific Review Panel discussed OSRA model inputs, climate change and modeling. A brief summary of several major workshop discussion points is provided below. This is followed by a more in-depth discussion and specific recommendations organized by project objectives (recommendations are highlighted in bold text).

4.1 Workshop Summary

4.1.1 Circulation

- Correctly simulating stratification is important to correctly simulating upper ocean circulation, including downwelling and upwelling, and eddy formation.

- Thickness of the upper layer above stratification is key to correctly transferring momentum from wind to ocean.
- Vertical gridding may require higher resolution in the deeper water, where the Pacific and Arctic Ocean interact, in order to simulate the water column T, S correctly; and thus the upper ocean circulation.
- Mass, heat and freshwater transports through the Bering Strait are critical to understanding Arctic Ocean circulation
- Atlantic water intrusion into the Arctic and freshening of the Beaufort Gyre (due to increased sea ice melt and river runoff) are both key factors in determining Arctic Ocean circulation

4.1.2 Meteorology

- Climate change has altered the atmospheric circulation
- A diminished Arctic sea ice canopy is shown to reduce albedo and lead to further warming.
- The diminished sea ice canopy should also lead to increased moisture flux and subsequent increase in precipitation over the Arctic and elsewhere in the hemisphere, leading to an increase in albedo
- Changes in the strength of the Beaufort gyre are related to winds and storm tracks

4.1.3 Sea Ice

- Changes in ice free conditions in some areas and seasons have been observed
- Temporal and spatial scales of the ice free periods, and overall ice motion is important to OSRA.
- Landfast ice from satellite observations is included in OSRA
- Sea ice ridging may also play an important part in the ice mass balance. Ridges are formed through the deformation of ice leads and the edges of ice floes. The leads in particular may be viewed as potential ice factories.

4.1.4 IPCC Scenarios and Models

- The IPCC models should be culled to consider only those models that do well for surface currents in the Arctic (e.g., Wang and Overland, 2009)

- Perform downscaling of IPCC models to produce boundary conditions for ocean circulation models.

4.1.5 AOMIP Results and Re-analysis of Hindcast Data

- Hindcast forcing data sets may be the best available for model inputs and model comparisons
- Use extreme cases to provide bounds on climate change effects
- Some simulations might be incorporated directly into OSRA

4.2 Discussion and Recommendations – Project Goals

4.2.1 Current status of oceanographic knowledge in the Arctic, including existing research in Arctic Ocean modeling and the quality of available forcing data for OSRA.

The Arctic Ocean hydrographic data is sparse in temporal and spatial coverage. Recently, the climatology has expanded in two ways. First, historical hydrographic data have been declassified and released by both Russian and western sources in the form of smoothed, three-dimensionally gridded fields for summer and winter (Environmental Working Group Atlas, EWG, 1997, 1998). This represents a significant advance but unfortunately, the data for these atlases were averaged for the decades of the 1950s, 1960s, 1970s and 1980s, irregardless of climatic regimes. Second, the Arctic hydrography database has expanded recently due to an increase in the number of high-latitude cruises and the establishment of several long-term observational sites in key regions, including major ocean boundaries (Bering Strait, Fram Strait, Straits of the Canadian Archipelago). Additional observations have been made in the vicinity of the North Pole (NPEO, 2011) and in the Western Arctic (Beaufort Gyre Observing System, BGOS, http://www.whoi.edu/beaufortgyre). There has been at least one major expedition by either icebreaker or submarine into the deep Arctic Ocean nearly every year between 1992 and 2011 (data are posted at the BGOS web site www.whoi.edu/beaufortgyre) and especially during 2007-2008 International Polar Year (IPY).

Other data include current velocity measured at moorings in the major Arctic Ocean straits and key regions of the deep basins. There are more than 900 months of these observations available just from the Institute of Ocean Sciences, Canada (Greg Holloway, personal communication: see data archive at: www.whoi.edu/project/AOREC). Other sources include the Alfred Wegener Institute, the Polar Science Center, University of Washington, and Ohio State University.

Significant amounts of data have already been incorporated into the data archives at the WHOI. These data (http://www.whoi.edu/science/PO/arcticgroup/projects/andrey_project) include climatologic information from the EWG atlas and specially selected and gridded T&S data provided by the scientists of the Arctic and Antarctic Research Institute, Russia, for different circulation regimes and for particular years. Completely new data are available from the NPEO and BGOS observing systems. Since 2004 the BGOS archive includes data from a new instrument, the Ice-Tethered Profiler (ITP), which repeatedly samples the properties in the upper 800 m of the ocean at high vertical resolution over long time periods. The instrument, its performance in the field, and examples of the data returned from the system are presented at http://www.whoi.edu/itp. These instruments in combination with the Arctic Ocean observing activity and IPY studies have been recovering an unprecedented amount of data from this region. To process and utilize this huge amount of information and make it available for the scientific community, methods of data assimilation need to be developed and validated for the region. Sea surface height data could be obtained from satellite altimetry (C.K. Shum, Ohio State University) for the regions of ice free ocean and from approximately 71 coastal tide gauges along the Northern Sea route (http://www.whoi.edu/science/PO/arcticsealevel).

There also are numerous other sources of data containing water temperature and salinity fields; sea ice thickness, concentration, and drift; sea level; and ocean currents. These data are located in NSIDC, ARCSS, NODC and at the new data archive established by NSF for observations under the Arctic Observing Network, AON. The Cooperative Arctic Data and Information Service (CADIS) supports the AON. It is a portal for data discovery and provides near-real-time data delivery. The above mentioned data are in extensive use by different modeling projects that assimilate these data, validate model results against observations to assess model errors and their uncertainties. Observational data are also used for processes studies and for investigations of climate change in the Arctic Ocean. In addition, there are ongoing studies collecting surface current data using high-frequency radars and satellite-tracked drifters in the Northeast Chukchi Sea. These data sets are supplemented by gliders measuring hydrographic properties and moored current meters measuring the subsurface circulation. In aggregate these new measurements represent a substantial increase the data available for comparison with models for this region.

There are several model intercomparison projects (MIP) working to improve Arctic models (e.g. Arctic climate MIP (ARCMIP), the Arctic Ocean MIP (AOMIP), and the coupled ARCMIP (CARCMIP, which tests truly coupled atmosphere-ice-ocean-land models). The MIPs are optimal tools for system integration, especially when they are carefully and diligently validated against observations. One outcome of MIP's activity is a better understanding of the strengths and weaknesses of different models, information that can then be used to assess future predictions and to guide fully coupled climate model development. For example, AOMIP studies are leading the way in directing the improvement of ocean models and needs for additional observations. Improvements in modeling tides and eddy parameterization are high on the list of importance. It is important that most of AOMIP models have been calibrated and validated based on observations available from the Chukchi and Beaufort Sea regions. Currently, the mostly dense data coverage is reached in these regions.

Recommendation 1: Improve data coverage to understand changes in major environmental parameters important for the OSRA mission:

- **Organize OSRA mission-oriented data archive to be used for both climate change studies and model calibration and validation purposes;**
- **Identify data gaps and organize observations in collaboration with other agencies to make data available to other parties including modeling teams and national and international data archives;**
- **Organize data collection from oil, gas, etc. commercial companies and data sources to avoid data duplication and redundancy;**
- **Analyze data with a major goal to understand rates of changes based on observations only.**

4.2.2 Validation of hindcast data currently used for OSRA and evaluation of the skill assessment against observations used to evaluate the surface currents in the region

Validation of the hindcast data currently used by OSRA includes output from the Rutgers coupled ice-ocean model. It should also include the set of accomplishments obtained by AOMIP (ocean) and atmospheric modeling teams working toward improvements of atmospheric reanalysis over the Arctic (WRF work performed by UAF, Polar WRF model employed by J.

Cassano from University of Colorado and an Arctic atmospheric reanalysis project lead by David Bromwich from Ohio State University).

Recommendation 2: Improvement of OSRA tools (models and forcing)

- **For the region under OSRA interest, reconstruct at least monthly (weekly or daily, if possible) atmospheric, sea ice and oceanic conditions (T, S, surface circulation) for the period of rapid climate change (1990 – present) employing coupled ice ocean models with data assimilation capabilities (assimilating observations of sea ice, sea surface heights, T-S time series and fields, ocean currents) to obtain sea ice drift and surface currents with minimized errors;**
- **Employ different (2-5) regional arctic coupled models for reconstructions of environmental parameters and estimate uncertainties (model errors) in the reproduction of observed fields and based on analysis of differences among model results;**
- **Investigate rates of sea ice (concentration, thickness, drift) and surface ocean circulation changes and determine errors of trends and observed changes;**
- **Run OSRA models with reconstructed forcing and evaluate changes in oil spill risk assessments since 1990 to present.**

4.2.3 Effects of climate change on sea ice, circulation, river discharge, etc. in the Arctic Ocean and the impacts of these changes on surface circulation

Effects of climate change on sea ice, circulation, river discharge, etc. in the Arctic Ocean and the impacts of these changes on surface circulation can be evaluated only employing regional (or better yet global models with high resolution) coupled ice-ocean models after running under conditions of specially designed numerical experiments. In these experiments, the role of a particular factor could be estimated by model runs with and without this factor influence or with different intensities of the investigated factor. These studies will elucidate the sensitivity of the models to various parameterizations or forcings. In so doing the results will suggest what mechanisms are most important in controlling model response. This will also guide inferences on how OSRA may respond to different climate change scenarios as projected by IPCC studies, noting that the IPCC projections are uncertain. Note also that forecast models are not exact and display a wide variance among themselves; so much so that they cannot be relied upon for applications with OSRA in the near term. There is question if the long term climate forecasts make adequate accounting of particulate contamination of the atmosphere and subsequent surface from soot. Some climate models a few years ago forecast a sea ice free Arctic by the middle of the current decade. There is a negative trend over the past decade in the extent of the sea ice canopy. Sea ice coverage though diminished significantly in 2007 was increasing in 2008. This means that IPCC model results have to be used with caution assuming that range of uncertainties in these predictions is large.

Recommendation 3: Estimate uncertainties in OSRA results. Perform a sensitivity analysis to determine how OSRA conditional probabilities change with respect to changes to climate variability and the complexity of ocean circulation models (emphasis on forecast circulation results). Develop circulation cases that test specific expected changes, - look to IPCC to formulate a range of test cases.

4.2.4 Alternate approaches for OSRA forcing

While IPCC forcings are too coarse to satisfy OSRA simulations and also assuming that IPCC model results have problems with accuracy of reproduction of sea ice and ocean parameters (including surface currents) it is possible to use IPCC forcing parameters outside the Arctic domain and to employ regional climate models to improve regional forcing based on downscaling procedures. As it was mentioned above (see section 4.2) there are regional polar WRF models allowing to "correct" IPCC atmospheric parameters and then to use regional climate models (like RACM described in W. Maslowski presentation in section 3.4.2) to obtain future forcing satisfying OSRA needs for future several decades.

Recommendation 4: Downscale IPCC forcing for OSRA. Consider if IPCC scenarios and their associated modeling results combined with regional reanalysis of climate system models could be used for providing forecast circulation data to OSRA

4.3 Concluding Comments

Projects resulting from recommendations for further studies and modeling approaches can be costly. Thus, some sensitivity tests for OSRA might be addressed. This might consist of running multiple model hindcasts, using statistics over 5 year (or other time scale) periods to see if these make a difference at the level of OSRA conditional probabilities. The OSRA runs might use specific years or a cluster of years, presumably after 1982 when the Rutgers calculations began.

Ice conditions are becoming more difficult to forecast, so this needs to be considered in climate scenarios to simulate with OSRA. This is important for selection of extremes rather than using a single prediction (because of high uncertainty in forecasting ice conditions) for input fields to OSRA. OSRA has some methodologies now: (1) Landfast Ice Zone Mask, seasonal and (2) Special algorithm for oil in the moving pack ice, oil moves with the ice for concentration ≥80% ice. A case study of no sea ice in the Arctic could also be considered, recognizing that such a circumstance would not occur out of context with other changes in the ocean and atmosphere. In addition, consideration should be given to explore how IPCC scenarios and their associated modeling results could be leveraged for providing forecast wind data to OSRA.

The workshop was successful in bringing together knowledgeable and interested parties – balanced in both science discipline and number of participants. It may be useful to repeat this workshop, perhaps in a year or two.

5.0 References

BOEMRE, 2010, Alaska Annual Studies Plan, U.S. Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement, Alaska Outer Continental Shelf Region, Anchorage, Alaska October 2010

BOEMRE, 2011. Oil Spill Modeling Program, http://www.boemre.gov/eppd/sciences/osmp/

Cox, P., and D. Stephenson (2007), Climate change: A changing climate for prediction, Science, 317, 207– 208.

Ekman, V.W. 1902. Om jordrotationens inverkan pa vindstrommar i hafvet. Nyt Magazin for Naturvidenskab 40 (1): 1–27.

Environmental Working Group (EWG), 1997. Joint U.S.-Russian Atlas of the Arctic Ocean for the Winter Period [CD-ROM], Natl. Snow and ice Data Cent., Boulder, Colorado.

Environmental Working Group (EWG), 1998. Joint U.S.-Russian Atlas of the Arctic Ocean for the Summer Period [CD-ROM], *Natl. Snow and ice Data Cent.*, Boulder, Colorado

Hawkins, E. and Sutton, R., 2009. The potential to narrow uncertainty in regional climate predictions, B. Am. Meteor. Soc., 90, 1095, doi:10.1175/2009BAMS2607.1

Hedstrom, K.S. 2009. Technical Manual for a coupled sea-ice/ocean circulation model (version 3). OCS Study MMS 2009-062.

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

Holloway, G. 2008. Observing global ocean topostrophy, J. Geophys. Res., 113, C07054, doi:10.1029/2007JC004635.

McPhee, M.G., Proshutinsky, A; Morison, J.H., Steele, M., and Alkire, M.B., 2009. Rapid change in freshwater content of the Arctic Ocean. Geophysical Research Letters. 36 (2009): L10602.

Nansen, F. 1902. Oceanography of the North Polar Basin, Sci. Res. Norweg. N. Pol. Exped. 1893-96, Vol. 111, No. 9, 427pp.

North Pole Environmental Observatory, (NPEO) 2011. http://psc.apl.washington.edu/northpole/

Overland, J., Walsh, J., Wang, M., Richter-Menge, J., Comiso, J., Meier, W., Nghiem, S., Perovich, D., Proshutinsky, A., and Morison, J., Arctic Report Card 2008: Tracking Recent Environmental Changes. Publications, Agencies and Staff of the US Department of Commerce. 2008.

Reynolds, R.W., T.M. Smith, C. Liu, D.B. Chelton, K.S. Casey, and M.G. Schlax, 2007. Daily high-resolution blended analyses for sea surface temperature. J. Clim., 20, 5473–5496.

Roberts, A., J. Cassano, R. Döscher, L. Hinzman, M. Holland, H. Mitsudera, A. Sumi, J. E. Walsh, 2010: A science plan for regional Arctic system modeling. International Arctic Research Center Tech. Paper 10–0001, 47 pp. [www.iarc.uaf.edu/publications/ reports/IARCTP10-0001.pdf.]

Steele, M., W. Ermold, and J. Zhang, 2008.Arctic Ocean surface warming trends over the past 100 years, Geophys. Res. Lett., 35, L02614, doi: 10.1029/2007GL031651

Steele, M., J. Zhang, and W. Ermold, 2010. Mechanisms of summertime upper Arctic Ocean warming and the effect on sea ice melt, J. Geophys. Res., 115, C11004, doi: 10.1029/2009JC005849.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze, 2007. Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34, L09501, doi: 10.1029/2007GL029703.

Wang, M., and J. E. Overland, 2009. A sea ice free summer Arctic within 30 years? Geophys. Res. Lett., 36, L07502, doi: 10.1029/2009GL037820

Woodgate R. A., K. Aagaard, T. J. Weingartner, 2005. Monthly temperature, salinity, and transport variability of the Bering Strait through flow, Geophys. Res. Lett., 32, L04601, doi: 10.1029/2004GL021880

Zhang, J., U. S. Bhatt, W. V. Tangborn, and C. S. Lingle, 2007. Climate downscaling for estimating glacier mass balances in northwestern North America: Validation with a USGS benchmark glacier, Geophys. Res. Lett., 34, L21505, doi:10.1029/2007GL031139.

Zhang, X., A. Sorteberg, J. Zhang, R. Gerdes, and J. C. Comiso, 2008. Recent radical shifts of atmospheric circulations and rapid changes in Arctic climate system, Geophys. Res. Lett., 35, L22701, doi: 10.1029/2008GL035607

Zubov, N. N. 1945. L'dy Arktiki [Arctic ice]. Moscow, Izdatel'stvo Glavsevrnorputi

Appendix A. Workshop Attendees

Evaluation of the Use of Hindcast Model Data for OSRA in a Period of Rapidly Changing Conditions
WORKSHOP
March 29-31, 2011

last name	first name	Organization	email	phone
Amstutz	David	SAIC	amstutzd@saic.com	540 854-5583
Beegle-Krause	CJ	Environmental Research for Decision, Inc.	cjbk@research4d.org	206 484-0004
Broje	Victoria	Shell Projects and Technology	victoria.broje@shell.com	281 544-7437
Collins-Ballot	Heather	ConocoPhillips, Alaska	Heather.S.Collins-Ballot@conocophillips.com	907 265-6213
Crowley	Heather	BOEMRE	heather.crowley@boemre.gov	907 334-5281
Galt	Jerry	Consultant	jerryg@genwest.com	360 403-7979
Holloway	Greg	Canada DFO	Greg.Holloway@dfo-mpo.gc.ca	250 363-6564
Ji	Jeff	BOEMRE	jeff.ji@boemre.gov	703 787-1145
Johnson	Walter	BOEMRE	walter.johnson@boemre.gov	703 787-1642
Konkel	Wolfgang	ExxonMobil Biomedical Sciences, Inc.	wolfgang.j.konkel@exxonmobil.com	908 730-1015
Lai	Ronald	BOEMRE	ronald.lai@boemre.gov	703 787-1714
Li	Zhen	BOEMRE	zhen.li@boemre.gov	703 787-1721
Maslowski	Wieslaw	Naval Postgraduate School	maslowsk@nps.edu	831 656-3162
Meier	Walter	NSIDC	walt@msidc.org	303 492-6508
Proshutinsky	Andrey	WHOI	aproshutinsky@whoi.edu	508 289-2796
Ray	Robert	Shell Projects and Technology	robert.raye@shell.com	713 245-7595
Samuels	William	SAIC	samuelsw@saic.com	703 676-8043
Smith	Caryn	BOEMRE	caryn.smith@boemre.gov	907 334-5248
Steele	Mike	University of Washington, APL	mas@apl.washington.edu	206 543-6586
Wang	Muyin	University of Washington	Muyin.Wang@noaa.gov	206 526-4532
Watabayashi	Glen	NOAA	glen.watabayashi@noaa.gov	206 526-6324
Weingartner	Tom	University of Alaska	weingart@ims.uaf.edu	907 474-7993
Yetsko	Chris	ConocoPhillips, Alaska	chris.m.yetsko@conocophillips.com	218 293-4114
Zhang	Xiangdong	University of Alaska	xdz@iarc.uaf.edu	907 474-2675
Zhang	Jing	North Carolina A&T	jzhang1@ncat.edu	336 285-2337

Appendix B. Speaker and Scientific Review Panel Bios

CJ Beegle-Krause, President, Research4D

Dr. CJ Beegle-Krause is the president of Research4D. Research4D is a nonprofit organization dedicated to research to provide further useful information for decision makers related to marine issues. Research4D views the best available science as providing the tool to make the most informed decisions, though frequently more than science needs to be considered. The organization's research interests are primarily oil spill related, but these activities have synergies with search and rescue, larval transport modeling, pelagic habitat and cruise ship discharges. Previous to coming to Research4D, CJ was a senior scientist at Applied Science Associates (ASA), where she developed biological behavior and oil interactions models, 4D visualization, larval fish trajectory modeling, and a "Synthesis of Knowledge". Earlier in her career, she was a lead trajectory modeler with the National Oceanic and Atmospheric Administration/Office of Response and Restoration (NOAA/HAZMAT), where she was on call 24x7 for spills across the U.S. and some foreign events airline disasters and some search and recovery operations. She started out her career as a marine biologist, and spent a summer with John C. Lilly's Human-Dolphin Foundation, and a year with the West Australia Maritime Museum.

Heather Crowley, Oceanographer, Bureau of Ocean Energy Management Regulation and Enforcement, Anchorage, AK

Dr. Crowley is an oceanographer with the Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE), Alaska OCS Region, Anchorage, AK. She is the BOEMRE Program Manager for the "Evaluation of the Use of Hindcast Model Data for OSRA in a Period of Rapidly Changing Conditions" Project. Dr. Crowley works in the Environmental Studies Program to establish the information needed for assessment and management of potential impacts from oil and gas development on the Outer Continental Shelf (OCS) and coastal environments. This includes predicting, projecting, assessing and managing potential effects on the human, marine and coastal environments of the OCS that may be affected by oil and gas development. She coordinates plans and studies with other ongoing programs and research projects, both internal and external to BOEMRE, to assure optimal studies management and efficient use of funding resources.

Greg Holloway, Senior Researcher, Fisheries and Oceans Canada, Pacific Region, Institute of Ocean Sciences, Sidney, Vancouver Island, British Columbia

Dr. Holloway has participated in the intercomparison of modeled drift of the Beaufort Sea gyre, and examination of the temporal differences required for climate warming versus cooling. He has also contributed to the very important work of the Arctic Ocean Model Intercomparrison Project (AOMIP). His recent work addresses the fresh water content of the Arctic Ocean, the thinning of sea ice and estimation of surface wind stress in the Arctic. He is the author of many papers concerning physical oceanography and modeling ocean dynamics, to include the modeling of differential transfers or heat and salt.

Walter Johnson, Oceanographer, Bureau of Ocean Energy Management Regulation and Enforcement, Herndon, VA

Dr. Walter Johnson is an oceanographer with the Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE) Herndon, Virginia. He performs oil spill modeling for the Oil Spill Risk Analysis (OSRA) used by BOEMRE in environmental documents. The BOEMRE assesses oil-spill risks associated with offshore energy activities off the U.S. continental coast and Alaska by calculating spill trajectories and contact probabilities. These analyses address the likelihood of spill occurrences, the transport and fate of any spilled oil, and the environmental impacts that might occur as a result of the spill. The BOEMRE OSRA model combines the probability of spill occurrence with a statistical description of hypothetical oilspill movement on the ocean surface. Prior to BOEMRE, Dr. Johnson was at the University of Alaska, Fairbanks, in the Institute of Marine Science, doing research on the coastal ocean in the Gulf of Alaska, Kotzebue Sound and the Chukchi Sea.

Wieslaw Maslowski, Professor of Oceanography, Naval Postgraduate School, Monterey, CA

Dr. Maslowski's research interests include: (1) Arctic Oceanography, (2) Sea Ice Dynamics and Thermodynamics, (3) Numerical Ocean and Sea Ice Modeling, (4) Ocean General Circulation and (5) Climate Change and Prediction. He is a member of many scientific boards including the National Academies of Science / National Research Council Committee on "A Science Plan for the North Pacific Research Board", the NSF Committee for the Bering Sea Initiative, and the Arctic Region Supercomputing Center Technology Panel. His teaching interests include: Descriptive Physical Oceanography, Polar Oceanography, Dynamical Oceanography and Numerical Modeling

Walt Meier, Research Scientist, National Snow and Ice Data Center, Boulder, CO

Dr. Walt Meier is a research scientist at the National Snow and Ice Data Center (NSIDC), part of the University of Colorado at Boulder. His research focuses on studying changes in sea ice using satellite remote sensing methods and investigating the impacts of sea ice on climate. He has been at NSIDC since 2003. Previously he held positions as an adjunct assistant professor at the U.S. Naval Academy in Annapolis, MD and as a visiting scientist at the U.S. National Ice Center in Suitland, MD. He is involved in: (1) researching potential of AMSR-E imagery to derive high-resolution sea ice motions and detect small-scale dynamic processes, (2) studying impact of earlier melt onset on the Arctic summer sea ice cover and correlation with minimum sea ice extent and (3) collaborating with UCAR visiting scientist Mingrui Dai to improve a simple sea ice forecast model that assimilates observed data to improve predictions.

Andrey Proshutinsky, Senior Scientist and Affiliate Professor, Woods Hole Oceanographic Institution, Woods Hole, MA

Dr. Proshutinsky's primary research interests are focused on research of the Arctic climate system and climate change through investigation of the Arctic Ocean Oscillation (AOO) and its interaction with the North Atlantic Oscillation (NAO) and the North Pacific Oscillation (PAO). He has been examining the climate variability and interactions between environmental parameters and processes in the Arctic through the use of combination of field work, statistical analyses of results, and numerical models. Dr. Proshutinsky is also investigating the shelf circulation of the Chukchi Sea and large scale changes in the Bering Sea. He has experience in numerical modeling of Arctic ice and ocean dynamics including tides, storm surge and applications to ship routing. His current primary focus is on climate system and climate change through investigation of the Arctic Oscillation and North Pacific Oscillation, two regimes of 4 to 6 year duration.

Mike Steele, Senior Oceanographer, Polar Science Center, Applied Physics Laboratory
University of Washington, Seattle, WA

Dr. Steele is interested in the large-scale circulation of sea ice and water in the Arctic Ocean. He uses both observational data and numerical model simulations to better understand the average circulation pathways as well as the causes of interannual variations in these pathways. His analysis of ocean observations has focused on the upper layers, which are generally quite cold and fresh. One aspect of his research focuses on the sources and sinks of this relatively fresh ocean water, the movement of this water within the Arctic Ocean, and its fate once it leaves the Arctic. Another topic of Dr. Steele's research is the effects of sea ice retreat on the properties of the upper Arctic Ocean. Specifically, he is looking at the warming of the upper ocean during summer. Dr. Steele is also collaborating with biological oceanographers to better understand how changes in ocean salinity and temperature are affecting arctic plankton and thus the marine ecosystem. Dr. Steele has active field programs in which data are collected in the field by his team and others, using aircraft, ships, and autonomous sensors like buoys and profiling floats. He is also involved with efforts to improve computer models of the Arctic marine system, via the Arctic Ocean Model Intercomparison Project, AOMIP.

Muyin, Wang, Research Meteorologist. Joint Institute for the Study of the Atmosphere and Ocean, University of Washington and NOAA

Dr. Wang’s primary research is focused on climate change, specifically: (1) climate processes in middle and high latitudes of the Northern Hemisphere, (2) impacts of climate change on ecosystems in the Pacific basin (including the Bering Sea) and Arctic, (3) components of Arctic climate system and their interactions among each other, (4) assessment of global coupled atmosphere-ocean climate models and (5) detection and attribution of climate change. Dr Wang is the lead author on a recent article published in Geophysical Research Letters (2009), "A sea ice free summer Arctic within 30 years?" Her current research projects include: (1) BSIERP/BEST (Bering Sea Integrated Ecosystem Research/Bering Ecosystem Study), (2) AYK (Arctic-Yukon-Kuskokwim Sustainable Salmon Initiative), and (3) Arctic Change Detection Synthesis Study of the Bering Sea – EcoFOCI.

Thomas Weingartner, Professor, University of Alaska, Fairbanks

Dr.Weingartner's present research activities include obtaining an understanding of variations in transport, and heat and salt fluxes through Bering Strait. Long-term measurements of these are required because these fluxes affect the thermohaline structure and biological productivity of the Arctic Ocean. Moreover, the Bering Strait plays an important role in maintaining the global hydrologic balance. In addition he is conducting research to understand how dense water that is produced during the formation of sea ice is transported and mixed as it flows across arctic shelves and slope. This effort involves an extensive mooring program on the northern Bering Sea shelf designed to test theoretical predictions on how these processes occur. Another topic of interest is the physical oceanography of Alaska continental shelves and slopes, including water mass transformation processes and inter-annual variation in Bering Strait fluxes.

Jing Zhang, Associate Professor**,** NOAA ISET Center, NC A&T State University

Dr. Jing Zhang is an associate professor of Atmospheric Sciences at ISET where she continues to pursue her research interests in numerical weather and climate modeling study. Specifically, her recent and ongoing research studies include: near real-time weather forecasting; mesoscale meteorological modeling study of the Chukchi and Beaufort Seas surface wind field; regional climate modeling and downscaling for studying the responses of glacier mass balance to future climate, and investigating social vulnerability to climate change in the coastal zone; storm-activity-induced atmosphere-sea ice-ocean interactions and their upscaling contribution to climate change; and climate impacts of a greener north. Through these efforts, she aims to gain better understanding of the weather and climate system.

Xiangdong Zhang, Research Associate Professor, International Arctic Research Center, University of Alaska, Fairbanks

Dr. Xiangdong Zhang is a research associate professor at the International Arctic Research Center, University of Alaska Fairbanks. He is interested in climate variability and global warming forced climate changes. Specifically, his recent research projects have focused on Arctic-global climate interactions and rapid climate change, tropical and North Pacific decadal variability, global warming forced extreme climate and weather events, Arctic and global freshwater and energy budgets and pathways, storm track dynamics and its interaction with large-scale circulations, and treatment/parameterization of physics in climate model. He has collaborated with national and international colleagues in his studies. The recent major representative accomplishments include the detection of spatial shift of atmospheric circulation and its driving role in the recent rapid Arctic climate change, identification of poleward shift of storm track and intensification of storm activity, evaluation of future Arctic sea ice changes by the IPCC AR4 models, and analysis of Arctic sea ice mass balance, heat and freshwater budgets and pathways.