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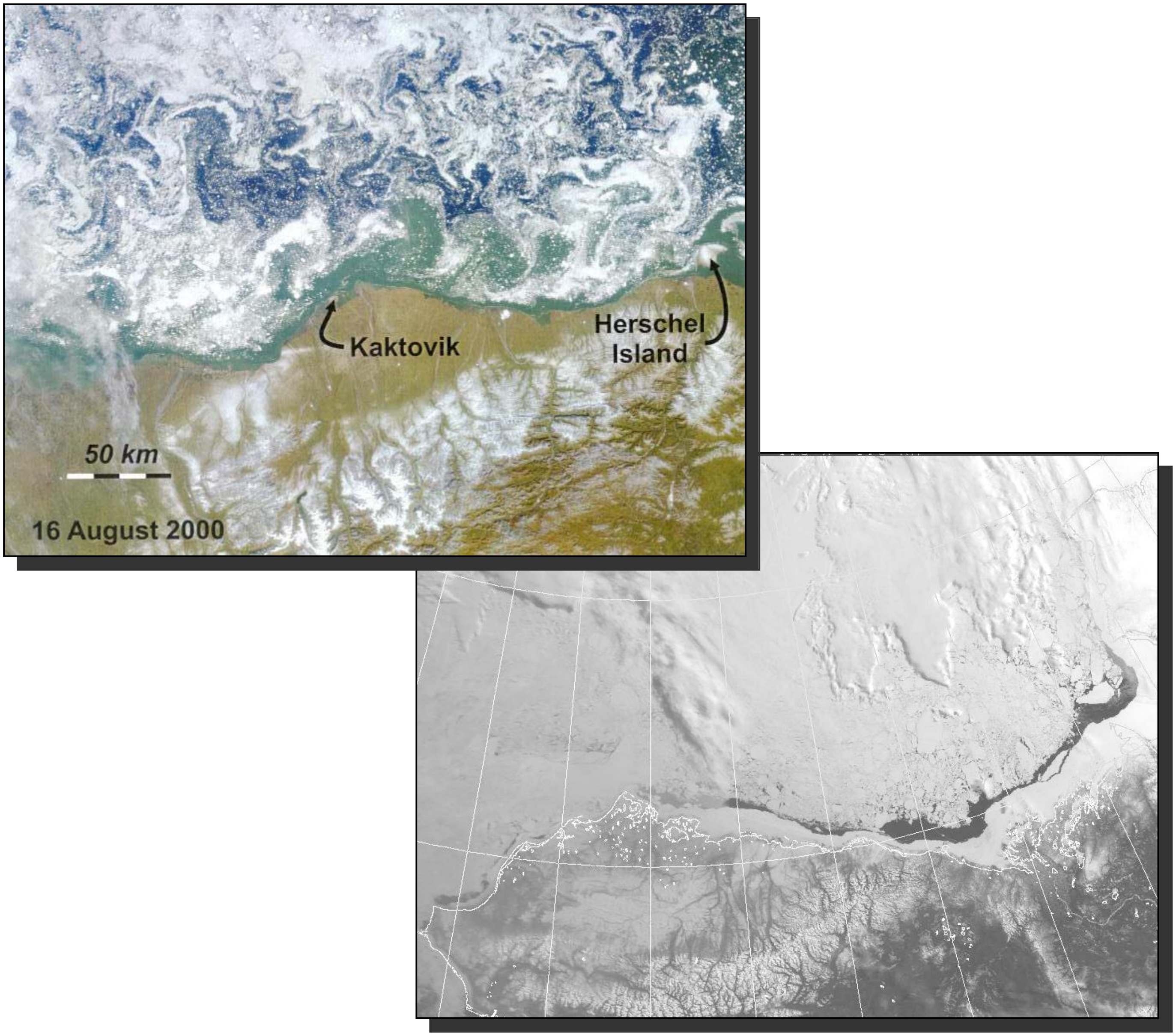
MMS 2003-045

PHYSICAL OCEANOGRAPHY OF THE BEAUFORT SEA

Workshop Proceedings



U.S. Department of the Interior
Minerals Management Service
Alaska OCS Region

OCS Study MMS 2003-045

ALASKA OCS REGION

PHYSICAL OCEANOGRAPHY OF THE BEAUFORT SEA

WORKSHOP RECOMMENDATIONS

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Workshop Chair

February 4, 5, and 6, 2003

Chena River Convention Center
Fairbanks, Alaska

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BEAUFORT SEA PHYSICAL OCEANOGRAPHY WORKSHOP

ABSTRACT

This report summarizes the results of a 2.5-day workshop on the physical oceanography of the Alaskan Beaufort Sea, held in Fairbanks, Alaska in February 2003. Dr. Thomas Weingartner, University of Alaska Fairbanks, served as chair of the workshop. The workshop reviewed knowledge of the physical oceanography of the Beaufort shelf and recommended studies to support Minerals Management Service's mission with respect to industrial development on this shelf or along the coast. There are fundamental unknowns pertaining to the ocean and ice circulation, ocean density field, and the forcing mechanisms that influence sea ice and ocean dynamics. The study recommendations consist of a mix of field (observational) and idealized model studies to improve understanding of poorly understood physical processes and boundary conditions and to provide data sets necessary for the proper evaluation of regional pollutant transport models. Critical issues requiring study are the:

1. wind and surface stress fields established by mesoscale variations in the regional meteorology and sea ice distribution and deformation fields,
2. effects of freshwater discharge and freezing (convective) processes on the shelf circulation,
3. controls exerted on the circulation and water property fields by the lateral ocean boundaries of the Alaskan Beaufort Sea: the Chukchi shelf (western boundary), the Canadian Beaufort shelf (eastern boundary), and the shelfbreak and continental slope (offshore boundary), and
4. shelf/slope bathymetry.

These topics affect the time and space scales of the ice and ocean circulation, which have not been well-resolved in the Beaufort Sea. Consequently, the recommended studies are also designed to delineate the major scales of spatial and temporal variability.

BEAUFORT SEA PHYSICAL OCEANOGRAPHY

WORKSHOP RECOMMENDATIONS

INTRODUCTION

This report summarizes the study recommendations developed from a 2.5 day workshop on the physical oceanography of the Alaskan Beaufort Sea, held in Fairbanks, Alaska from February 4 - 6, 2003. The purpose of the workshop was to review our present understanding of the regional oceanography and to provide a set of study recommendations in support of the Minerals Management Service's (MMS) mission. The MMS manages development on the U.S. Outer Continental Shelf, including oil and gas leasing, exploration, and development. The agency conducts environmental studies to predict, project, assess, and manage potential effects on the human, marine, and coastal environments of the Outer Continental Shelf and coastal areas that may be affected by oil and gas development. The task before the workshop was not to anticipate what types of development might occur, but to provide guidance on what physical environmental processes need to be understood in order to predict how development might affect (and be affected by) the marine environment. In addition the workshop considered what knowledge is necessary to anticipate how climate changes might alter the present state of the Beaufort Sea's physical environment.

The participants believe that there are fundamental unknowns in our understanding of the circulation, thermohaline fields, and the forcing mechanisms important to this shelf's dynamics and the ability to predict pollutant transport and dispersal. A variety of observations and models indicate that the Arctic Ocean is undergoing substantial environmental change. These changes, which are reflected in the atmosphere, the sea ice, the ocean, and in terrestrial processes might be associated with global warming and/or a response to low-frequency climate variations. The Beaufort Sea shelf may be particularly sensitive to climate variability. While an assessment of these broad-scale changes is beyond its purview, MMS must be prepared to respond to future changes. In developing the recommendations, the attendees considered the types of information needed that would lead to rapid advances in the predictive skill of regional circulation models that can be used to understand present conditions and to plan for the future. In order to develop such models, the recommended studies will:

1. Guide model development by increasing our understanding of important physical processes,

2. Enhance model skill by providing more realistic boundary conditions and forcing fields, and

3. Provide data sets necessary for model evaluation.

The recommendations include a mix of observational studies and idealized process modeling. The latter are relatively simple theoretical models (analytical or numerical) designed to identify fundamental physical principles, spatial and temporal scales, and features of oceanic phenomena. Such models are needed for: (1) helping to interpret field observations, (2) potentially guiding new field programs and (3) improving the physical principles and parameterizations necessary to enhance the predictive skill of regional circulation models.

Our recommendations refer to the western, central, and eastern Beaufort Sea (Figure 1). Although these are subjective designations, the sub-regions underscore the attendees' sense that there are significant differences across these regions. These differences imply along- and cross-shore gradients in ocean and ice forcing, water properties, circulation, and stratification. Understanding and quantifying these differences are essential for realistically predicting pollutant transport and dispersal.

For the purposes of this report, we refer to the Alaskan Beaufort Sea shelf as the region between the coast and the continental slope between Pt. Barrow and the U.S.-Canadian border (Figure 1). The shelfbreak describes the region seaward of the 50 m isobath and includes the continental slope (to a depth of ~2500 m). The inner shelf is defined as the region shoreward of the 50 m isobath, and includes the coastal zone. The latter lies between the coast and about the 20 m isobath and includes most of the landfast ice zone. The

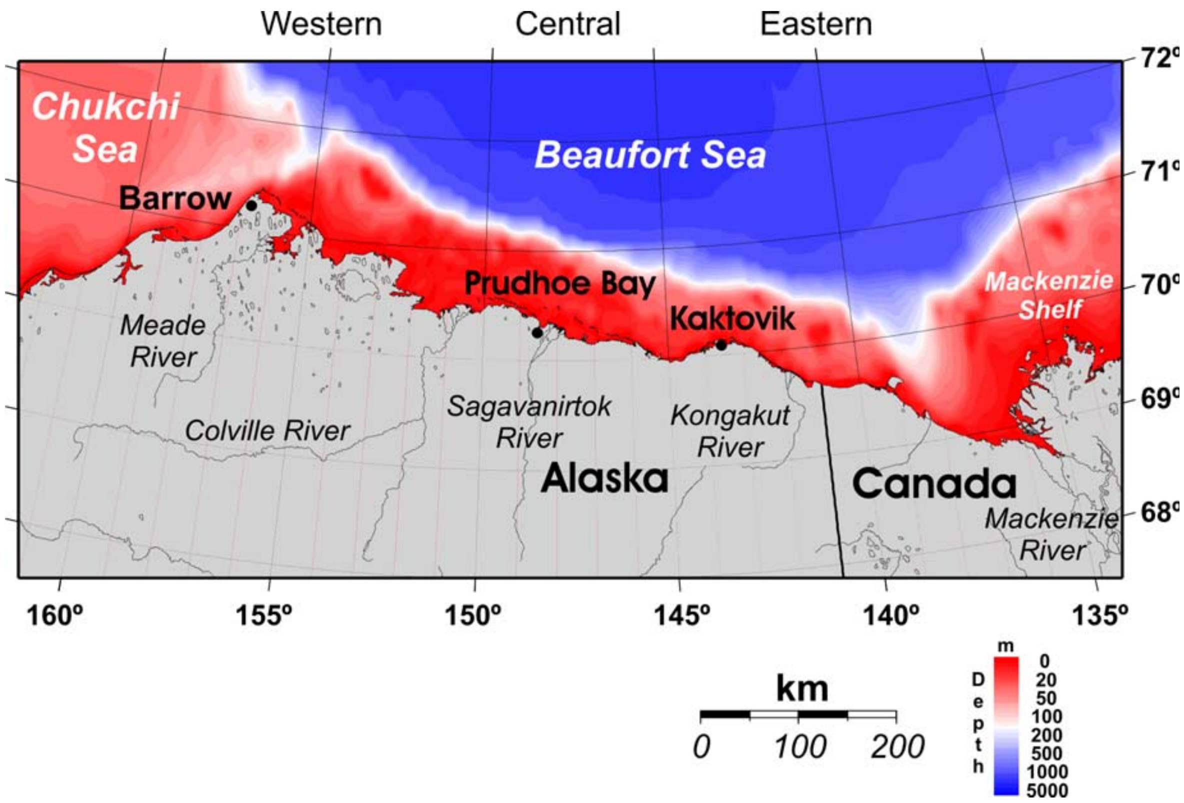

Figure 1. Map of the Alaskan Beaufort Sea and North Slope with place names and subdivisions indicated. The coast extends 550 km eastward from Pt. Barrow to the Canadian boundary. The width of the shelf from the coast to the 200 m isobath is approximately 100 km.

landfast ice zone also includes the highly deformed stamukhi zone typically located between the 20 and 25 m isobaths.

The recommendations are ordered by topic (assigned a Roman numeral) under which one or more specific studies or questions are listed by number. Many of the topics are implicitly related to one another. Where connections are made they are cross-referenced by a parenthetical note. For example , Topic I.1 refers to the first study recommendation from Section I Surface Winds and Stresses.

I. Surface Winds and Stresses

Accurate specification of the surface wind and stress field is essential to predicting ocean and ice circulation. The Beaufort Sea shelf is likely subject to substantial along- and cross-shore gradients in the surface wind velocity with these gradients possibly involving changes in both wind speed and direction. At present, wind gradients are not captured adequately by winds derived from synoptic pressure fields (typically prepared by weather forecasting and climate centers) and/or extrapolated from coastal meteorological stations, both of which are often used in estimating the shelf wind field. Two important effects requiring attention are the mountain barrier baroclinity influence imparted by the Brooks Range in winter and the sea breeze effect established by land-ocean-sea ice thermal gradients in summer. The mountain barrier effect primarily influences the eastern and central portions of the shelf, whereas the sea-breeze phenomenon likely extends the length of the coast. The magnitude and the along-shore and cross-shore gradients of these phenomena are inadequately known. Oil spill models that rely on winds measured from coastal stations or from synoptic pressure fields could be seriously biased.

A further complication stems from inadequate knowledge of the sea ice distribution and its dynamics. Sea ice covers the Beaufort shelf for at least nine months of the year and mediates the transfer of momentum from the winds to the ocean through ice-borne stresses. The majority of sea ice mechanics studies have been conducted in the central basin where the ice stress distribution is isotropic (the statistical properties of the stresses do not vary significantly with position and the stresses have no preferred direction) and quasi-stationary. On the shelf however, large and complex lead systems, spatial gradients in ice thickness, and the landfast ice result in highly non-linear, non-stationary, and anisotropic stresses. Consequently it is unlikely that ice mechanics principles developed for the central basin apply to the shelf.

Recommendations:

1. Mesoscale meteorological model studies of the mountain barrier and sea breeze effect need to be conducted in conjunction with appropriate observations (including a thorough review of historical data from the Beaufort Sea DEW line sites and recent MMS-supported meteorological measurements) of the shelf wind field to determine the spatial scales (both along- and cross-shelf) of wind variability, the sensitivity of the mesoscale wind field to ambient conditions (including the large scale synoptic fields and the broad scale distribution of ice), and their frequency of occurrence. Additional permanent meteorological stations should be installed along the Beaufort coast to augment the present measurement sites of Barrow and Deadhorse Airport. At present these are the only two locations permanently collecting meteorological data along the 600 km of coast bordering the Alaska Beaufort Sea. (This is a distance equivalent to that between Los Angeles and San Francisco where there are at least 15 NOAA marine meteorological buoys!) Permanent coastal recording stations should at least be installed between Barrow and the western side of the Colville River delta and at Kaktovik (Barter Island). These stations are essential for estimating the wind-field over the nearshore Beaufort Sea and also for assessing the alongshore variations in the coastal wind field.

2. Observations are needed of the sea ice distribution (thickness and concentration), ice velocity, and deformation fields over the shelf. These sea ice properties substantially influence ice mechanics and the stress distribution over the shelf (and therefore ocean and ice circulation). Satellite data can contribute to this effort, but the high spatial and temporal resolution needed requires an in situ observational study. Study suggestions include deploying arrays of relatively inexpensive GPS/radio transponders or satellite tracked buoys in an experimental program to measure ice velocity and deformation fields in both the landfast and pack ice. A coastal ice radar system can provide complementary information at the high spatial resolution necessary to assess the evolution and dynamics of the inner shelf ice field.

3. The preceding recommendation should be conducted in conjunction with transmitting (and possibly expendable) meteorological stations that measure surface winds both across and along the shelf. Such stations could be deployed simultaneously with transponders fixed into the ice.

4. These observational programs should be undertaken in conjunction with ocean-ice circulation process models. The modeling activity would consist of sensitivity studies that specify the spatial resolution of the wind and stress fields needed to characterize the circulation. The modeling effort would include the circulation response to both up- and downwelling favorable wind fields with variations in the position and properties of the ice and ice edge. The model studies should incorporate representations of the background flow and stratification characteristic of the Beaufort Sea.

II. Coastal Boundary: Buoyancy-forced Coastal Circulation

The Beaufort Sea shelf is subject to large annual variations in both positive and negative buoyancy forcing. (Positive buoyancy forcing refers to processes that decrease seawater density and negative buoyancy forcing refers to processes that increase seawater density.) The former includes the large seasonal discharge cycle of Alaskan North Slope rivers, the seasonal melting of sea ice, and the possibly substantial year-round freshwater contribution from the Mackenzie River in the eastern Beaufort (Topic III.B). The North Slope river discharge, which is concentrated in the central and eastern portions of the coast, increases rapidly from zero in late May to a maximum in June (when landfast ice is still intact) and then decreases to zero discharge by late October. The river discharge forms strongly stratified freshwater plumes and/or coastal currents. The stratification profoundly influences the vertical transfer of momentum through the water column. Plumes and coastal currents also have complex horizontal density and circulation fields, such as fronts, meanders, and eddies that could accumulate or rapidly disperse material across and along the shelf. These motions are inherently related to water density differences and they could disperse pollutants in a manner inconsistent with inferences drawn solely from knowledge of the wind field.

An understanding of the transport and dispersal of freshwater on the Beaufort shelf is further complicated by the presence of landfast ice, which inhibits wind-mixing of the river plumes and ambient seawater. The ice also introduces an inverted bottom boundary layer at the upper surface of the plume, which would substantially influence plume circulation dynamics. Virtually nothing is known about the behavior of river plumes beneath landfast ice.

Negative buoyant forcing occurs in fall and winter during cooling and freezing and results in convection and vertical mixing that erodes the stratification. The development of sea ice and the breakdown in stratification changes the momentum distribution over the water column and therefore the characteristics of the wind-driven circulation. Negative buoyancy forcing can also generate dense water gravity currents and eddies that alter the wind-forced circulation. This forcing is not uniformly distributed over the shelf because the seaward progression of landfast ice through fall slows ice growth and hence convection in the coastal zone. Convection therefore varies spatially and temporally in accordance with changes in the ice distribution.

Recommendations:

1. A critical issue relevant to both types of buoyancy forcing is the extent to which these processes enhance or inhibit transport across the landfast/pack ice margin. Buoyancy forcing in conjunction with spatially varying wind and ice stresses could be important in effecting this exchange although it is not known if substantial exchange occurs. This issue should be addressed using idealized process models that determine if substantial exchange occurs and how such exchange is accomplished. Observational efforts that concentrate on basic descriptions of the ice and ocean structure and circulation should commence with the modeling effort because such information will be required during the early phase of modeling activities. A more comprehensive field effort would eventually follow and be developed from the results of the modeling studies using different types of buoyancy- and wind-forcing and ice conditions.

2. A closely related issue pertains to the behavior of freshwater plumes spreading beneath the landfast ice. Sampling underice plumes (horizontal and vertical properties) is a desirable yet difficult undertaking. Appropriate field measurements should be designed based on the results of idealized process models that examine the evolution of underice freshwater plumes. The model results would provide guidance on how far offshore and alongshore the river plume would extend under conditions that include surface (e.g., the ice bottom) and bottom friction and weak ambient flows associated with low frequency motions, tides, and offshore winds. The models should also include the influence of winds offshore of the landfast ice, the damming effect established by the stamukhi zone, and variations in underice topography. The latter is poorly known but should be obtained by mapping the under-ice topography in an experimental study area.

3. Better estimates are needed of the freshwater discharge cycle for North Slope rivers. River gauging is impractical, especially during breakup when maximum discharge occurs, but hydrologic (stage-discharge) models are probably sufficiently mature to provide reasonably good estimates of the seasonal phasing and volume of the discharge needed for regional circulation models. Model estimates of these parameters need to be made for (at least) the larger North Slope rivers.

4. Observations of the three-dimensional circulation and thermohaline field associated with the river discharges are needed during the open water period. The focal area of such a study should be in the central or eastern Beaufort (where most of the rivers discharge). An integrated field program involving ocean surface current mapping radars, satellite tracked drifters, ship-borne surveys with a towed instrument package (to examine the 3-dimensional thermohaline structure), air-borne salinity mapper (surface salinity distribution), moorings (for the vertical velocity structure), and satellite imagery are all appropriate tools for examining this important but unknown aspect of the shelf circulation. The measurements should cover a variety of spatial (<1 km - 100 km) and temporal scales (hours - months) and extend over the width of the shelf and cover an alongshore extent of at least 100 km.

5. Although salinity provides a measure of the amount of freshwater on the shelf it cannot, by itself, identify freshwater sources. Geochemical techniques can discriminate between riverine water and sea ice and it appears likely that the geochemical properties of the Mackenzie River differ from Alaskan North Slope rivers. Insofar as waters from the Mackenzie shelf might importantly influence the Alaskan Beaufort Sea (TOPIC III.B), a comparison of potentially useful geochemical tracers from these different river systems is recommended. This comparison could be efficiently accomplished in conjunction with the NSF-sponsored PARTNERS program now underway by including samples from Alaskan North Slope rivers. Once the appropriate suite of geochemical tracers are determined, future hydrographic studies of the Beaufort shelf (TOPIC III C.1) should routinely include geochemical sampling to discriminate among freshwater sources.

6. Based on cursory satellite image analyses of ice conditions in the Alaskan Beaufort Sea it appears that flaw lead development, although common on the Mackenzie shelf, is less frequent on the Beaufort shelf. However, as a step towards understanding the dynamical importance of convection in the Alaskan Beaufort Sea a comprehensive review of satellite imagery for this shelf needs to be undertaken. This review should include a statistical analysis of the lead frequency, geographic and seasonal distribution of major lead systems, and the synoptic atmospheric conditions under which leads and the landfast ice/stamukhi zone form. This information would be helpful in guiding the model studies described in TOPIC II.1 are relevant to issues described in TOPIC I.2 and I.3.

III. LATERAL OCEAN BOUNDARIES

Topics III A, B, and C address the western, eastern, and offshore oceanic boundaries of the Alaskan Beaufort Sea shelf. These boundary processes affect the transport of ice, water, and materials on and off the Beaufort shelf as well as cross- and along-shelf flow and property gradients, which might be substantial on the Alaskan Beaufort Sea shelf. While convenient to think of the ocean boundaries as separate entities, they are dynamically linked to one another via the ocean circulation, surface stress fields, bottom friction, and processes occurring internally on the Beaufort Sea shelf. For example, both the Chukchi Sea (western boundary) and the Mackenzie shelf (eastern boundary) contribute waters to the offshore boundary (shelfbreak), with this boundary controlling the along-shelfbreak structure of the circulation and density fields. In turn these fields influence and are modified by eddy formation, the bottom boundary layer, and cross-shelf exchanges. Moreover, the boundary influences vary seasonally because of changes on similar time scales in the circulation and water masses flowing along the boundaries.

The exchange of pack ice between the shelf and the basin might also be an effective means for transporting contaminants. Indeed, buoyant contaminants can be entombed in growing ice and transported without weathering over long distances. Heavier contaminants buried in sediments or adsorbed to particles can be re-suspended during autumn storms, incorporated into growing ice, and subsequently transported. Sediment-borne contaminants may also be re-suspended by ice keel gouging.

Understanding these various connections requires an integrated observational program that addresses these regions and exchanges in aggregate. There are also specific issues associated with each boundary deserving of separate study that could be conducted independently of a more integrated study.

A. Western Boundary Oceanographic Influences

Barrow Canyon lies along the western boundary of the Alaskan Beaufort Sea, and is the division point between the Chukchi and Beaufort shelves. Some fraction of the Chukchi shelf outflow, which includes waters from the Bering Sea carried northward through Bering Strait, flows northeastward through Barrow Canyon and thence eastward along the Beaufort Sea shelf, shelfbreak, and slope. The Chukchi outflow probably exerts important dynamical influences on the circulation over the Beaufort shelf, although the spatial and temporal extent of these influences are not well understood.

B. Eastern Boundary

As discussed in Topic I winter winds over the eastern Beaufort Sea might be quite different (at least occasionally) than those over the central and western portions of the shelf. In addition the eastern Beaufort shelf adjoins the Canadian sector of the Beaufort Sea, where oceanographic conditions are profoundly influenced by year-round runoff from the Mackenzie River and possibly by water upwelled onto the shelf through the Mackenzie Canyon. Substantial quantities of Mackenzie River water have been measured as far west as the Northwind Ridge and Chukchi Cap (north of the Chukchi Shelf) suggesting that the Mackenzie influence might extend over the entire Beaufort Sea shelf. The coastal zone is also an important migratory corridor for whitefish (a subsistence food fish) that migrates between the Mackenzie and Colville rivers.

C. Offshore Boundary

Beaufort Sea shelfbreak processes exert important dynamic controls on the shelf circulation and are important in controlling exchange between the shelf and the deep basin. These processes are primarily influenced by the structure of the uppermost 500 meters of the water column. Several different water masses are advected along the shelfbreak in a vertically and horizontally sheared current system. The surface layer contains Arctic Ocean mixed layer waters and Chukchi/Bering summer waters moving westward within the southern limb of the Beaufort Sea Gyre. (Note however, that in summer and fall Chukchi/Bering summer water is also moving eastward on the Beaufort Sea shelf and over the shelfbreak). Beneath this ~50 m thick layer is an eastward flow of Chukchi/Bering waters and, at greater depths, eastward flowing waters of Atlantic Ocean origin. The subsurface eastward flow extends onshore to at least the 50 m isobath. However, along-shelf gradients in wind-forcing (including upwelling and downwelling) and cross-shelf mixing (induced by shelfbreak eddies which carry shelf water into the Arctic Ocean basin) can change the along-shelf distribution of density and momentum, with concomitant implications for exchanges with the inner shelf.

Recommendations IIIA, IIIB, IIIC:

1. Appropriate moored and shipboard measurements of currents, sea-ice drift, and hydrography (including geochemistry) are needed across the Beaufort Sea shelf to examine the large-scale circulation and density fields. In light of the large interannual variations in winds and ice conditions this must be a multi-year study. Current observations must be made across the shelfbreak and inshore of the 50 m isobath and include the near-surface (using, for example, moored Acoustic Doppler Current Profilers [ADCPs] and profiling temperature and salinity instruments). These measurements need to be conducted simultaneously across the shelf in the western, central, and eastern Beaufort Sea so that a synoptic view of the circulation is achieved. Mooring measurements should be supplemented with cross-shelf hydrographic (with a station spacing of less than 5 km) ADCP and/or towed vehicle transects along several sections spanning the breadth of the Beaufort Sea at least during the open water season. This study should proceed in phases. We recommend that a beginning effort include collaborating with Canadian and Japanese scientists on their research vessels, which are annually working in the Chukchi Sea and Canadian Beaufort Sea. (Note these vessels are unlikely to proceed inshore of the 20 m isobath so additional logistical support will be required for nearshore sampling.) Extra sampling time should be supported on these vessels to (synoptically) sample several cross-shelf transects in the Alaskan Beaufort Sea. These data would provide a preliminary description of along-shelf variability and guide the eventual deployment of instrumented moorings.

Recommendations for IIIA:

1. The interaction of the wind-driven flow on the Beaufort shelf (which is westward over much of the year and downwind) with the outflow from Barrow Canyon needs to be determined. It is not known if the canyon outflow is primarily confined to the shelfbreak or if some of it spreads eastward over the inner Beaufort shelf to converge with the wind-driven westward flow of the Beaufort shelf. The nature of this interaction will likely vary in accordance with changes in wind forcing and with seasonal changes in the canyon transport. A modeling study that covers the parameter space of canyon transport and wind-forcing needs to be performed to examine variations in this interaction. These results would guide additional future observational efforts.

Recommendations for IIIB:

1. Mackenzie river runoff might infiltrate along the eastern Alaskan Beaufort Sea in the coastal zone. Year-round current measurements need to be made in this region with these measurements supplemented by periodic geochemical and salinity sampling to determine if Mackenzie River water enters this area year-round.

IV. MISCELLANEOUS RECOMMENDATIONS

A. Bathymetry

Ocean circulation and ice translation and deformation processes depend very sensitively upon the bathymetry, which is not well known for the Beaufort Sea shelf. Sustained efforts are needed to develop accurate bathymetric maps for the Beaufort and there are numerous vessels plying the waters of the Beaufort Sea by which these data can be acquired. While such opportunistic measurements might not meet the requirements for navigational charting, they would be more than adequate for the purposes of science and modeling. We recommend that an initiative be established to co-ordinate a "bathymetry of opportunity" program. This initiative would consist of a team that would coordinate data collection from US, Japanese, and Canadian vessels operating in the area. The team's responsibilities would also include compiling, performing quality control, and improving a Beaufort Sea bathymetric database for scientific purposes. We recommend that this activity be performed in collaboration with the IOC's International Bathymetric Chart of the Arctic Ocean (IBCAO) so that their bathymetric products can be updated. Additional recommendations are:

1. Assemble bathymetric data collected by industry. While we understand that there might be proprietary issues regarding these data, we are willing to write and co-sign a letter to industry in support of efforts to obtain these data.

2. Coordinate data collection from vessels of opportunity (USCG, CCG, supply tugs, research vessels). Many of these are equipped with GPS and digital sounders so that this data can be easily collected and stored during vessel operations in the Beaufort Sea.

3. Support the processing and analysis of the extensive bathymetric data set collected by Dr. Margo Edwards (U. Hawaii) during ONR-supported SCICEX cruises along the Alaskan Beaufort shelfbreak.

B. Tides and storm surges

Although tides on the Beaufort Sea shelf do not appear to exert an important dynamical influence on this shelf's oceanography, they might be important with respect to ice dynamics. Storm surges influence coastal erosion and might affect landfast ice breakout events (breakout is when the landfast ice detaches from its nearshore anchor point and either drifts freely or deforms). Routine measurements of storm surges and tides (sea level and currents) provide useful points of comparison for ice-ocean circulation models. For example, we expect that tidal properties will change seasonally in response to seasonal changes in water column stratification and ice cover. To the extent possible, field measurements (especially time series measurements) should sample at sufficiently high temporal resolution so that the storm surge and tidal constituent properties can be resolved.

C. Long-term monitoring

The Beaufort Sea is subject to large seasonal and interannual variations in its sea ice and oceanographic properties. This natural variability will be modulated by longer-term climate changes. For example, climate predictions indicate that the sea ice characteristics of the Arctic Ocean and its adjacent shelves will change substantially in the future with significant alterations in water mass properties and circulation accompanying changes in the sea ice regime. Characterizing these variations is essential if we hope to assess the potential impact of present and future marine industrial development.

Many of the preceding recommendations will enhance our understanding of the natural variability and provide guidance on how to efficiently monitor this shelf ecosystem. We recommend, however, that two additional steps be taken now. First, we recommend that a modest nearshore monitoring program begin with moored instruments (temperature, salinity, sea-level, and currents) deployed at several alongshore locations. Suggested sites include near Barrow, Prudhoe Bay and Kaktovik and the sites should be selected in consultation with biologists knowledgeable of important habitats. (For example, the Boulder Patch in Stefansson Sound might be deemed an important monitoring site given its unique biological characteristics.) Although biological sampling was not within the purview of this workshop, we note that a biological component is a requirement of such monitoring.

Second, we recommend that selected areas of the shelf and shelfbreak be monitored. This could be initiated through collaboration with Japanese and Canadian scientists who have long-term regional research interests. This effort might initially involve annual hydrographic surveys, but should eventually be expanded to include long-term moored instrumentation capable of sampling year-round. In particular, the results from these monitoring activities need to be interpreted in the context of larger scale environmental change in the Arctic. Such efforts appear to be underway under the auspices of the NSF and NOAA, providing opportunities for leveraged monitoring in the Beaufort Sea.

WORKSHOP PRESENTATION SUMMARIES

INTRODUCTORY REMARKS

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The Minerals Management Service is a bureau of the Department of the Interior whose responsibilities include the management of offshore oil and gas developments in federal waters; in Alaska these waters extend from three miles offshore and beyond. The MMS aims to regulate oil and gas development in an environmentally sound and safe manner, thereby minimizing or altogether preventing damage to natural marine resources. One of the fundamental goals of the MMS is environmental assessment. MMS environmental impact statements predict consequences of exploring oil and gas and evaluating alternative strategies. The overall mission of the environmental studies programs is to establish information necessary and useful for the assessment of impacts on human, marine, and coastal environments of the OCS.

Currently, a five-year program is underway to implement potential planning areas on the OCS subject to leasing within the next five years. Five of eight proposed areas are more likely to be offered: Beaufort Sea Sale 186 (2003), Cook Inlet/Shelikof Strait Sale 191 (2004), Beaufort Sea Sale 195 (2005), Cook Inlet Shelikof Strait Sale 199 (2006), and Beaufort Sea Sale 202 (2007). It is the duty of MMS to identify, monitor and understand any changes in these areas subsequent to leasing and development. Of particular interest and a key component of the environmental impact statement will be oil spill risk analysis, in which physical oceanography plays a vital role.

Inclusive of the MMS's goals to assess environmental impact with regards to oil and gas exploration is the utilization of advancements in physical oceanography. Computer modeling has become a powerful tool in assessing environmental hazards such as sea ice, storm surge, strudel scour, ice gouging, river breakup and flooding of sea ice, as well as contaminant transport by local and long distance transport by wind, water, and ice. Predictions can be made on oil spill dynamics, which can then be analyzed and used for oil spill response and response planning. Furthermore, physical oceanography is an important science that will help us better understand ocean ecology and may allow us to calculate predictions in global change and/or Arctic cycles.

The MMS operates in part on suggestions for research by institutions, other agencies and research scientists. MMS has been working toward goals set by the 1990 National Academy of Sciences review, where applicable and relevant. Continued support for poorly understood oceanographic and meteorological processes and oil spill risk analysis, reduction of reliance on model results before they are verified with hard data, and close corroboration between field scientists and modelers in all future MMS programs are among suggestions made by the NAS in 1990. Under the Environmental Studies Program (ESP) National Strategic Plan, future oil spill research will include ocean transport and coastal and continental shelf currents. Data collected from these studies will be used to validate and improve the power of computer models.

There are two ongoing projects that will further enhance our knowledge in the development of physical oceanography: Nearshore Beaufort Sea Meteorological Monitoring and Data Synthesis Project and the Nowcast/Forecast model for the Beaufort Sea Ice-Ocean Oil Spill System.

In addition, the recent MMS Alaska OCS Region Workshop on Small-Scale Sea Ice and Ocean Modeling (SIOM) for Nearshore Beaufort and Chukchi Seas (MMS OCS Report 2003-043) held at the University of Alaska Fairbanks brought together scientists from all over the world to discuss and suggest future and further studies on ice mechanics and ice/ocean modeling in the Beaufort Sea.

PHYSICAL OCEANOGRAPHY OF THE BEAUFORT SEA: AN OVERVIEW

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The Alaska portion of the Beaufort Sea shelf extends ~650km eastward from Pt. Barrow to the Canadian EEZ. Bottom depths grade relatively smoothly from the coast offshore for ~100 km to the shelfbreak along the 200 m isobath. Its physical oceanography is influenced by a variety of "local" and "remote" processes involving the atmosphere, adjacent shelves, the Arctic Ocean basin, and freshwater discharge along the coast. These influences all vary seasonally leading to correspondingly large seasonal variations in the shelf's circulation, thermohaline structure, and sea ice.

The atmosphere plays a prominent role in the shelf circulation through the winds, which impart momentum to the ocean, and through the surface heat balance, which controls the annual cycle of freezing and melting over both the ocean and the land. Both processes influence the horizontal and vertical density structure of the shelf and slope. The wind stress and heat fluxes vary across the shelf because of the cross-shore sea ice distribution. From fall through early summer landfast ice occupies the inner shelf between the coast and the 20 m isobath, beyond which the ice drifts freely. In summer, ice retreats northward across the shelf, although the southern limit of the ice edge can vary tremendously from year-to-year. The cross-shelf gradient in sea ice distribution implies similarly large gradients in wind stress and buoyancy fluxes. The summer circulation is further by the impulse-like discharge from the numerous rivers that drain Alaska's North Slope. This discharge strongly stratifies the inner shelf at least until the land-fast ice breaks up.

The flow along the continental slope consists of an amalgam of water masses from different sources, including waters of Atlantic, Pacific and Arctic Ocean origin and possibly from the Mackenzie sector of the Beaufort Sea as well. Arctic Ocean waters flow counterclockwise around the Beaufort Sea occupying a relatively thin (50 – 75 m) layer over the shelfbreak. Atlantic waters, enter the Arctic Ocean through Fram Strait and flow counterclockwise along the margin of the Arctic Ocean beneath the surface layer. As it moves eastward around the basin, the outflows from the shelf seas of Eurasia and the Chukchi Sea intrude between the surface layer and the Atlantic Layer and progressively modify the thermohaline structure of the shelfbreak and slope. The outflow from the adjacent Chukchi Sea is particularly important because it varies seasonally in quantity and properties, with these effects transmitted along the Beaufort slope. The massive discharge from the Mackenzie River onto the Canadian Beaufort Sea is believed to extend onto the Alaskan shelf (at least in some years) suggesting that this outflow could be important in the regional oceanography.

Efforts to predict the regional circulation are complicated because few of these processes are understood in any detail and many of them are very sensitive to the changes that now appear to be occurring in the climate of the Arctic.

EXITS AND ENTRANCES - LARGE-SCALE ARCTIC OCEAN CIRCULATION AS A NEIGHBOR FOR THE BEAUFORT SEA

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The large-scale circulation of the Arctic Ocean can be considered in roughly four parts:

- the Arctic Ocean Boundary Current, which moves Atlantic (and other) waters cyclonically around the edges of the Arctic basins and along mid-ocean ridges,

- the interior gyre circulations, which are weak, scattered with eddies, fed by waters from the boundary current, and, at least at the surface, co-rotating with the sea ice,

- the ice motion, which consists generally of two counter-rotating gyres (cyclonic over the Eurasian Basin, anticyclonic over the Beaufort) with the position of the boundary between the gyres moving according to the state of the atmospheric Arctic Oscillation,

- the Pacific waters, which enter through Bering Strait and travel either northwards into the high Arctic or eastwards towards the Beaufort Sea.

Thus, the Beaufort Sea is supplied from the west with waters from the Chukchi Sea and the Arctic Ocean Boundary Current, and from the north by sea-ice and waters of the Canadian gyre. Similarly, waters exit from the Beaufort eastwards towards the Canadian Archipelago, Lincoln Sea and Fram Strait or, in the case of the ice and upper waters, westwards past Alaska.

Drawing on observations and modeling work, this talk will give an overview of the Arctic Ocean circulation, with emphasis on how it feeds into and from the Beaufort. Particular focus will be placed on the upstream inputs from the Chukchi Sea and the Chukchi Borderland. The latter, the region of complex topography including the Northwind Ridge and Abyssal Plain, and the Chukchi Cap and Abyssal Plain, acts as a "crossroads" for the Atlantic waters moving eastward in the boundary current and the Pacific waters entering from the south. Data from a 5-week hydrographic and mooring cruise in this region in autumn 2002 sheds light on communication pathways between the Beaufort Sea and the parts of the Arctic Ocean which lie to the west.

THE JOINT ROLES OF PACIFIC AND ATLANTIC-ORIGIN WATERS IN THE CANADA BASIN HALOCLINE: OBSERVATIONS FROM 1997 ONWARDS

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Canada Basin waters are observed to be in transition, responding primarily to the effects of upstream change in atmospheric and oceanic circulation. Data collected in the southern Canada Basin in 1997-98 show that the composition of Canada Basin waters, and in particular the composition of the halocline, can no longer be viewed as laterally homogeneous and in steady state. Observations obtained prior to the 1990s showed that the Canada Basin halocline occupied the upper 200 m of the water column and was comprised of three components: the upper and middle halocline which extend to 150 m and are of Pacific-origin; and the lower halocline which is of Atlantic-origin. In 1998 the halocline was thinner in the northwestern Canada Basin, occupying only the upper 150 m of the water column. Here, the Pacific-origin middle halocline was located in the top 75 m. Underlying Atlantic-origin lower halocline waters were fresher, colder and much more ventilated than observed in the past. These new observations of a sub-surface oxygen maximum suggest that outflow from the East Siberian Sea now supplies the Canada Basin lower halocline. East of the Northwind Ridge in the southern Canada Basin, the halocline was thicker and dominated the upper 250 m of the water column. Here the halocline was relatively unchanged and consisted of Pacific-origin upper and middle halocline waters in the top 225 m and Atlantic-origin lower halocline water.

Underlying the halocline, Atlantic Layer waters as much as 0.5 °C warmer than the historical record were observed over the Chukchi Gap and also over the northern flank of the Chukchi Plateau in 1998. These observations signal that warm-anomaly Fram Strait Branch waters, first observed upstream in the Nansen Basin in 1990, had arrived downstream in the Canada Basin and also indicate two routes whereby Fram Strait Branch waters enter the southern Canada Basin. Data collected in 2002 show that warmer waters have broached the Chukchi Borderlands and have entered the southern Canada Basin.

OBSERVATIONS AND MODELING AT REGIONAL SCALE: BEAUFORT GYRE

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The Beaufort Gyre (BG) is one of the most hostile and inaccessible areas of the globe. Most of it has never been measured or observed. The first oceanographic observations were made from ice floes by US aircraft in 1951 and 1952 (Worthington, 1953). The major feature discovered by Worthington was a large anticyclonic gyre (Beaufort Gyre) in the northern parts of the Beaufort Sea. Since 1951, there have been several expeditions sampling water characteristics and bottom sediments in the region: manned drifting stations T3 (1958 and 1965-70), Arlis (1960-61), AIDJEX (1975-1976), North Pole (1950-1991), SHEBA (1997-1998); buoys SALARGOS (1985-1993), IOEB (1996-1998), IABP (1979-present); airborne surveys (Sever, 1972-1986); submarine surveys (SCICEX, 1993-1998); and satellite-based observations (1972-present). In 1954, Treshnikov, using Russian airborne surveys, determined the boundaries of the BG. Gudkovich (1966) calculated the period of sea ice circulation in the BG (3.5 years) by analyzing Russian drifting station tracks. In 1974 Hunkins discovered subsurface eddies after extensive observations during the AIDJEX program. After AIDJEX, the first phase of BG exploration was completed and routine observations have been performed since 1978. This routine work brought new discoveries: in 1984 Aagaard discovered Beaufort Undercurrent in the beginning of the 1990s, warming of the Atlantic water layer and sea ice thinning relative to the 1970s, and a change in the rate of bioproductivity were recorded (Carmack et al., 1995; Rudels, et al., 1996; Swift et al., 1997; Rothrock et al., 1999, Melnikov, 2000). Despite these findings, the BG is still a relatively inaccessible region of the World Ocean. Most expeditions have obtained information describing some oceanic and biologic parameters from the upper most layers of the ocean and along the southern periphery of the BG. However, the central and northern parts of the Gyre are still poorly investigated. Ocean currents, ocean structure, and oceanic biological components deeper than the upper layer are not known. Spatial and temporal variability of the BG dynamics, sea ice parameters, bottom structure and sediments, biological productivity, and paleoceanography remain unknown in this area.

Numerical modeling in the area is limited by application of large-scale model results to the Beaufort Sea. The Arctic Ocean Model Intercomparison Project (AOMIP)* is an international effort recently established to carry out a thorough analysis of model differences and errors and to analyze major features of oceanic parameters in the areas without good observations. As far as may be judged, based on the conclusions of existing reports and publications – and in contrast to global climate models – regional Arctic Ocean models reproduce the basic dynamics and thermodynamics of the Beaufort Sea reasonably well; but when we compared our model results in 2001, we discovered that striking differences existed across models in nearly every parameter analyzed.

The discrepancies in salinity (of order several practical salinity units) were observed in the Beaufort Sea; surface water circulation was more or less comparable but the Atlantic Water circulation was reproduced differently by AOMIP models depending on model resolution and model physics. The problem is likely in the low model resolution because these models do not resolve eddy dynamics.

Recently, a new hypothesis (Proshutinsky et al., 2002) along with supporting evidence was introduced showing that the BG plays a significant role in regulating the arctic climate variability. Existing data analysis and numerical model results show that the BG may accumulate a significant amount of fresh water during one climate regime (anticyclonic) and may release this water to the North Atlantic during another climate regime (cyclonic). This hypothesis can explain the origin of the salinity anomaly periodically found in the North Atlantic as well as the BG role in the decadal variability in the Arctic. This leads us to the conclusion that it is extremely important to understand the structure of the BG water properties, its currents, and their variability in space and time. We encourage the creation of an internationally coordinated observational and modeling program to investigate the Beaufort Sea properties and variability.

* http://ish.cims.nyu.edu/project_aomip/overview.html.

SEA ICE OVER THE BEAUFORT SEA SHELF: CHARACTERISTICS AND SIGNIFICANCE FOR REGIONAL OCEANOGRAPHY

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The ice canopy of the Beaufort Sea is one of the more complex and dynamic sea-ice covers in the Arctic Ocean. The southern Beaufort Sea is dominated by first-year ice, with multi-year floes advecting into the area from the perennially ice-covered regions to the North and Northeast. Beginning in the late 1970's, summer minimum ice extent in the Beaufort and Chukchi Seas has decreased significantly, with record ice minima observed in recent years. Apart from exposing wider stretches of the continental shelf during summer, the retreating ice has also impacted the upper ocean's heat and salt budget. Both from the 1998 SHEBA experiment as well as a 2002 spring cruise as part of the Shelf-Basin Initiative (SBI) there is some evidence that heat fluxes to the ice bottom from trapped solar heat have increased, leading to reductions in first- and multi-year ice thickness. At the same time, the upper-ocean/ice system is also strongly impacted by variations in surface wind forcing and dispersal of Mackenzie river runoff. The coastal topography and prevailing anti-cyclonic surface circulation induce significant far-range ice-land interaction, leading to some of the highest ice deformation rates (specifically shear and vorticity) in the Arctic Ocean. This is reflected in the ice roughness and thickness distribution as well as in the stability and morphology of the coastal land-fast ice. The latter typically extends over several tens of kilometers in the Beaufort and <10 km in the Chukchi Sea and is of importance both in shutting down atmospheric momentum transfer and in defining the potential sites for polynya formation and resultant high ice-production/salt-release rates. Observations of large stretches of sediment-laden sea ice during the spring 2002 SBI cruise in conjunction with earlier studies can provide indirect insight into potential increases in the amount of wind and thermohaline mixing in coastal waters in winter as a result of changes in the ice and circulation regimes.

SPREADING PATHWAY OF EASTERN CHUKCHI SUMMER WATER IN THE WESTERN ARCTIC OCEAN

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The Atlantic Water (AW) inflow into the Arctic Ocean has been considered as a primary oceanic heat source affecting the variability of ice cover. This might be true in the Eastern Arctic Ocean, i.e. Nansen and Amundsen Basins, in some aspect. However the oceanic stratification in the Western Arctic Ocean is not identical to the Eastern one. In the Western Arctic Ocean, Pacific Summer Water (PSW) via the Bering Strait is primary heat source for ice cover rather than AW. PSW is classified into two distinct varieties Eastern and Western Chukchi Summer Waters based on the salinity range and pathway in the Chukchi Shelf. Among these two PSWs, Eastern Chukchi Summer Water (ECSW) carries sufficient heat within the upper layers of the ocean to significantly affect rates of ice cover and decay. The followings are our current understandings on the spreading pathway of ECSW.

(1) Most of ECSW is transported westward from the Northslope into the Chukchi Borderland (Northwind Ridge and Chukchi Plateau).

(2) The westward advection is done by two ways:

   (a) The detachment of ECSW accompanying large eddies occurs on the Northslope east of the Barrow Canyon (150-154W).

   (b) In general, easterly is strengthened during winter from December through February. This seasonal wind pushes the summer water toward the Northwind Ridge against the eastward buoyancy driven flow.

(3) Northwind Ridge and Chukchi Plateau are the two major pathways of ECSW from the southern Beaufort Sea into the central Canadian Basin.

(4) The Northwind Ridge corresponds to the western spreading boundary of the Mackenzie Water

(5) Salinity in the winter mixed layer over the Chukchi Borderland west of the spreading boundary of Mackenzie Water is nearly the same as of Eastern Chukchi Summer Water (~31psu).

(6) Then the heat of the ECSW can be released effectively in this region. The potential of the ECSW for ice melt reaches about 50cm over the Chukchi Borderland in the case of SHEBA period.

(7) These influences of ECSW appear in all climatological features such as subsurface temperature, sea ice thickness, and surface air temperature.

(8) The Chukchi Borderland would be one of important region where the Arctic change appears in early stage.

(9) Trans-Canada Basin drifting buoy data showed that some part of ECSW re-circulated into the Canadian Beaufort Sea. Some part of ECSW would outflow into the Canadian Archipelago.

VARIETIES OF TEMPERATURE MINIMUM WATER IN THE WESTERN ARCTIC OCEAN

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Observations presented here were made in the southern Canadian Basin aboard the CCGS Louis S. St-Laurent and R/V Mirai in 2002. In the Canadian Basin the salinity as temperature minimum has been identified as 33.1 psu. Pronounced minima in dissolved oxygen content are seen at the well-known temperature minimum. However, three distinct varieties of temperature minimum water are recognized on the basis of salinity and oxygen content: (1) temperature minimum and oxygen minimum water with S~33.1; (2) temperature minimum and oxygen maximum water with S~34.0; (3) temperature minimum and oxygen minimum water with S~34.0.

(1) is most general temperature minimum water in the Canadian Basin. Temperature/ salinity correlation plots show that temperature minimum core properties are smooth, and below temperature minimum temperature increases monotonically with depth to Atlantic Water. The oxygen-rich property of (2) suggests that this water is a newly ventilated water into the Canadian Basin. Ventilation is possibly to occur in the coastal area between Cape Lisburne and Point Barrow. During winter period, coastal polynya appears in this region by the offshore advection of sea ice due to strong easterly wind being associated with the seasonal variability of the Beaufort High. The last type (3) reveals the same feature as (2) in T/S scatter plots, i.e., these two types are difficult to distinguish using T/S properties. However a crucial difference appears in the value of dissolved oxygen around the temperature minimum. The low oxygen property of (3) suggests that this water ventilates somewhere far away from the Canadian Basin.

THE SENSITIVITY OF ARCTIC SEA ICE TO OCEANIC HEAT FLUX

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Approximately 5 million square kilometers of multi-year ice lie at the core of Northern Hemisphere pack ice. A thick layer of cold salt-stratified seawater that underlies much of this old ice is generally regarded as an important factor in its existence. The weak temperature gradient and strong density gradient within this cold halocline inhibit a flux of heat to the ice from warm layers deeper in the ocean.

The cold halocline is maintained through ventilation of the upper ocean by waters at freezing temperature, which are formed during the growth of new ice in winter. The mechanisms of ventilation within the two principal basins of the Arctic, the Eurasian and the Canadian, are thought to be slightly different. Although there are strong arguments for the importance of the cold halocline to Arctic ice, there is, to date, little direct evidence of this.

The Canadian polar continental shelf is an area of 3.3 million square kilometers, dotted with the islands of the Canadian Arctic Archipelago (1.4 million square kilometers). The ice of the Archipelago clears only slightly in summer an din winter becomes the largest area of land-fast ice in the world. Since the opportunity for new ice growth in this environment is small, cold instrusions into the halocline do not occur and the halocline warms progressively with distance from the Arctic Ocean. The Archipelago is thus a natural laboratory where the impact on ice of a warm halocline can be studied.

Ice thickness within the northern Canadian Arctic Archipelago was systematically measured (at 124,000 locations!) during the conduct of seismic surveys in the 1970s. These data reveal that ice emerging into the Northwest Passage after a transit of several years from the Arctic Ocean is a frail shadow of its former self. Average thickness has decreased by 40 % and heavily ridged ice is much less common.

The winters in the Archipelago are actually colder than in the Arctic Ocean and snow cover, another important influence, is about the same. Therefore, the probable cause of this dramatic change is the preferential melting of thick ice within the Archipelago in response to a sustained heat flux of 5-10 W m^{-2} through the warm halocline.

In a warmer climate, the duration of land-fast conditions within the Archipelago will likely decrease, so that the transit time for ice will decrease. With less time to melt, ice emerging into the Northwest Passage in the future may actually be more threatening to navigation than at present. This is not the conventional wisdom on the issue.

The cold halocline embodies an important feedback loop between ice growth and melt within the climate system.

SHELFBREAK CIRCULATION IN THE ALASKAN BEAUFORT SEA: MEAN STRUCTURE AND VARIABILITY

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While it is well established that a significant amount of Pacific-origin water enters Barrow Canyon from the Chukchi shelf, the fate of this water as it encounters the edge of the Canada Basin is uncertain. Dynamical constraints suggest that much of the transport should skirt the canyon, and continue to the east along the shelfbreak and upper slope of the Beaufort Sea. Here we show that this notion is likely correct, and use historical data to quantify the structure, transport, and variability of the “Beaufort shelfbreak jet.”

The available hydrographic sections from the National Oceanographic Data Center, over the period 1959-1987, are transformed into a bathymetric coordinate system and combined to form a mean thermal wind section for the Beaufort shelfbreak/slope. This is referenced using historical current meter data, revealing a jet on the order of 15-20km wide, centered near the 150m isobath. Seasonally, the jet varies between three distinct configurations. In spring/summer it transports cold winter-transformed Bering Sea water as a mid-depth jet. Later in the summer/fall it evolves into a buoyant, surface-trapped jet carrying warm Bering Sea summertime water. Finally, in late-fall and winter¾under upwelling favorable winds¾the Atlantic water flows eastward at relatively shallow depths along the upper slope. From year to year there can be marked changes in the first of these configurations, whereby the winter-transformed Pacific-origin water ventilates different strata within the halocline.

At mid-latitudes, shelfbreak jets undergo pronounced mesoscale fluctuations. We briefly discuss a few of the processes that lead to shelf-slope exchange of water, some of which are likely active in the Beaufort shelfbreak jet. One such process is baroclinic instability and eddy formation. Recently, a high-resolution hydrographic data set was obtained along the southern boundary of the Canada Basin as part of the Western Arctic Shelf-Basin Interactions (SBI) Program. Preliminary analysis of these data, within the framework of previous mid-latitude instability modeling, suggests strongly that eddy formation readily occurs along the shelfbreak of the Alaskan Beaufort Sea.

SHELFBREAK AND SLOPE PROCESSES IN THE BEAUFORT AND CHUKCHI SEAS

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Interactions among hydrographic structure, bathymetry, ice cover, river inflow and tidal and wind forcing allow a wide variety of physical process to effect shelfbreak and slope exchange in the Beaufort Sea and Chukchi seas. During the past decade it has become evident from physical, biological and geological observations that the shelfbreak regions of the Arctic margins are more energetic (and episodic) than initially suspected. In this brief overview a selection of examples is presented to illustrate this view; specifically:

- Massive upwelling events in Mackenzie Trough and subsequent generation of eastward progressing internal Kevin Waves
- Shelfbreak upwelling off Caper Bathurst and subsequent (apparent) enrichment of benthic communities off Whale Bluff.
- Wind-forced offshore export of Mackenzie River water and subsequent storage within the Beaufort Gyre.
- Tidal resonance and generation of baroclinic waves on the Northeast lobe of the Canadian Shelf and potential consequences to the production of food for bowhead.

In addition, recent biological and geological data collected during the JWACS 2002 program aboard the R/V Mirai are presented to emphasis the ‘interdisciplinary importance’ of physical exchange mechanisms. Biological data is presented to illustrate the role of Barrow Canyon in the export of chlorophyll and oxygen enriched water from the Chukchi into the adjacent ocean. Geologic data is presented to argue that sediments delivered to the Mackenzie are actively shunted across the Canadian Shelf into the adjacent Canada Basin.

Finally, speculations are presented on the possible response of Arctic shelves to climate variability on decade to millennium time scales.

THEORETICAL CONSIDERATIONS OF ALONGSHELF CURRENTS, UPWELLING AND THE ICE EDGE

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Subinertial currents over the Beaufort Shelf are likely to be dominated by two processes, alongshelf flows entering from the west and wind-driven upwelling. Currents that originate well to the west of the Beaufort Shelf tend to be topographically steered to produce eastward flows over the Beaufort Shelf. For example, most of the North Alaskan coastal current, which is itself a product of the Bering Strait throughflow, should turn eastward upon encountering the continental slope north of Pt. Barrow. Similarly, Atlantic water flowing eastward along the continental slope at the edge of the Chukchi Sea should continue along the slope of the Beaufort Sea. Baroclinic effects may alter this behavior somewhat, but not as easily as might be expected.

Competing with these eastward flows is the westward flow driven by the predominantly upwelling favorable winds over the Beaufort Shelf. Wind events can generate strong, narrow (10-15 km) westward jets over mid-shelf and at the shelf edge. Wind-driven upwelling also produces considerable exchange between the shelf and the deep basin, carrying saline water from the upper halocline onto the shelf. The strength of both the wind-driven alongshelf currents and the shelf-edge exchange may be strongly influenced by the location of the permanent ice pack during summer. Alongshelf currents and shelf-edge exchange are severely reduced if the ice edge is located shoreward of the shelf break.

Examples of these processes will be presented based on results from a primitive-equation numerical model in somewhat idealized settings.

WIND AND BUOYANCY FORCED MOTIONS ON SHALLOW, VERTICALLY STRATIFIED, INNER SHELVES

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A century ago Walfrid Ekman provided elegant analytical solutions on how frictional stresses impact the barotropic circulation both in the deep open and shallow coastal oceans (Ekman, 1905). A boundary layer scale emerges, the Ekman layer depth (~10-m), that can be compared with the local water depth. I define an "inner shelf region" as the area where the total water depth scales with this Ekman layer. Observations from this crucial region of land-shelf interactions evolved only over the last decade (Lentz, 1995) and emphasized a sizeable baroclinic contribution to the dynamics due to river discharges. Furthermore, it appears that the change of flow direction with depth (vertical veering) on inner shelves is much larger than predicted (Münchow and Chant, 2000). Numerical models frequently exclude the inner shelf and parameterize this dynamically active region through boundary conditions applied at a coastal wall of finite depth. The resulting flows on the shelf and beyond are very sensitive to these conditions as vertical veering of currents implies both along- and across-shelf flow components (Samelson, 1997; Münchow and Chant, 2000).

I here review unpublished inner shelf observations from the Mackenzie shelf in the Canadian Arctic where buoyant Mackenzie River waters induce strong vertical stratification in water generally less than 25-m deep. Wind speed and direction determine circulation, dispersion of particles (drifters), as well as vertical and horizontal density stratification. The spotty and not always synoptic data do not facilitate dynamical analyses or firm conclusions. It is not even clear how and when buoyant Mackenzie River waters leave the 140-km wide continental shelf to become entrained in the surface circulation of the Beaufort gyre. Do the buoyant waters just spread offshore in an "estuarine circulation" unaffected by rotation? Does the fresh water export take place in the form of ice? Or do a few upwelling favorable wind events in fall move buoyant waters westwards towards Mackenzie Canyon where they exit the shelf? Without a carefully designed study, we can't really tell. The available observations do provide a base, however, for comparative studies with shelf systems whose scales and dynamics are more easily studied and understood. We here use velocity and density observations from the Rio de la Plata (South-America) and the Mid-Atlantic Bight to place the Mackenzie shelf observations into a more general framework.

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NEARSHORE CIRCULATION ON THE ALASKAN BEAUFORT SHELF

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We measured current velocity, temperature, salinity, and transmissivity (a proxy for suspended sediment load) at hourly intervals for three years at from 3 -4 mooring sites in the nearshore region of the Beaufort Sea near Prudhoe Bay. The primary purpose of the program was to measure under-ice and open water currents for evaluating oil-spill trajectories and sedimentation risk in this nearshore environment. Mean currents are westward but weak (<3 cm-s^{-1}) and polarize in the along-shore direction. The mean currents vary little in magnitude seasonally, although there are two distinct seasonal circulation regimes. The open water/loose ice regime lasts from early July through mid-October during which time the currents are swift, highly variable, and significantly correlated with the alongshore winds. Current speeds typically exceeded 10 cm-s-1 and maximum currents can be greater than 100 cm-s^{-1}. The region is covered by landfast ice from mid-October through the end of June. Currents at this time were feeble (~3 cm-s^{-1}) and the current variations were primarily tidal. Less than 1% of the current speeds exceeded 20 cm-s^{-1} and less than 10% of the current speeds exceeded 10 cm-s^{-1}. Although semi-diurnal tidal variations account for the bulk of the current variations, the largest currents are associated with subtidal current fluctuations of 4 - 10 days duration, although these fluctuations are not correlated with the local winds. Currents are horizontally coherent throughout the year over the 35 km separating the moorings. Vertical current shears are weak beneath the landfast ice, but become significant during the spring freshet when river plumes spread beneath the ice and on occasion during the open-water period. Acoustic backscatter suggests that these plumes have a thickness of about 1.5 m and salt conservation budgets suggest that the plume salinity is <5 psu. We estimate that the salinity gradients might be as great as 28 psu/m. There are no significant sources of kinetic energy available for mixing when the landfast ice is present. Once the landfast ice retreats mixing is easily accomplished during summer wind events.

The transmissivity record indicates a frequently turbid nearshore environment during the open water season with re-suspension events occurring during storms. Although the suspended sediment load diminishes when landfast ice forms, there are nevertheless frequent events during which time sediment is either re-suspended or advected from elsewhere through the region. Under-ice river plumes also carry an enormous sediment load as transmissivity attained its minimum values during the spring freshet in June but before the landfast ice melted. Offshore currents associated with the underice plume are ~10 cm/s. The results suggest that the river plume and its associated suspended load could be carried at least 20 km offshore during the duration of the spring freshet.

GEOCHEMICAL TRACERS OF THE FRESHWATER COMPONENT OF BEAUFORT SEA CIRCULATION

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Geochemical tracers are widely recognized as an invaluable tool in modern oceanography. Combined with measurements of temperature and salinity, geochemical tracers provide information about ocean circulation and mixing processes that could not be derived from physical measurements alone. In the Arctic, a suite of conservative and quasi-conservative tracers – including nutrients (N, P, Si, alkalinity), oxygen isotopes ($\delta^{18}O$), and trace metals (e.g., Ba) – has been used to characterize water masses, define their boundaries, and quantify contributions from freshwater sources (sea ice melt and runoff from North American and Eurasian rivers) and marine waters of Atlantic and Pacific origin.

Tracer measurements have provided many insights into primary factors governing the Beaufort Sea system: the large discharge of the Mackenzie River, Pacific inflow via the Bering and Chukchi seas, ice formation and melting, and active biogeochemical cycling over the shelves. An example of this was the shelf-to-basin transect out to the original SHEBA site in 1997, at which unusually thin sea-ice and the presence of a shallow layer of low-salinity surface water beneath the ice was observed. Distributions of salinity, $\delta^{18}O$, and Ba along the transect quantified the contributions to the low-salinity layer from sea ice melt and Mackenzie River runoff [Macdonald et al., *DSR I*, 49, 1769-1785, 2002]. Another example is provided by the 1998 ARKTIS-XIV/2 *Polarstern* Expedition, during which measurements of salinity, $\delta^{18}O$, Ba, and nutrient ratios (N/P) were made along a section through Fram Strait. A mass balance based on these tracer distributions quantified contributions from sea ice melt, runoff from North American and Eurasian rivers, and marine waters of Atlantic and Pacific origin in waters exiting the Arctic downstream of the Canada Basin through Fram Strait [Taylor et al., *JGR*, in press].

THE WORKSHOP ON SMALL-SCALE SEA ICE AND OCEAN MODELING (SIOM) FOR NEARSHORE BEAUFORT AND CHUKCHI SEAS

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The workshop held during August 7-9 2002 at University of Alaska Fairbanks discussed the present status and future direction of small-scale sea ice and ocean modeling, leading to a working plan for the state-of-the-art sea ice and ocean modeling. The focus of the workshop was the future ice-ocean modeling and Minerals Management Service (MMS) needs in the inshore Beaufort Sea waters, including seasonal land-fast ice. The workshop produced recommendations on modeling approaches based on the updated advance in small-scale sea ice and ocean modeling.

The workshop had four research themes: sea-ice mechanics modeling, sea-ice dynamics, small-scale and basin-scale coupled ice-ocean modeling, and sea-ice/ocean observations. There were 32 presentations. Each theme had a rapporteur to chair the discussions and summarize the recommendations at the end of the workshop. The workshop produced approaches and recommendations for small-scale ice-ocean modeling over the next 5-10 years, which will be valuable for the Coastal Marine Institute and MMS missions and International Arctic Research Center-Frontier Research System for Global Change (IARC-FRSGC) modeling strategies. This workshop also promoted the collaboration between the US scientists, including those at IARC and Institute of Marine Science of UAF, and the international community.

The workshop has produced a working plan for the small-scale ice-ocean modeling over the next 5-10 years. The summary is as follows:

1. Although viscous-plastic (VP) ice model is generally good for the large-scale climate modeling, the recommendation is that a VP plus elastic (EVP) ice model would be better to both large-scale and small scale modeling.
2. Sea ice distribution for ridged ice and rafted ice should be used to better study sea ice of difference types (multiple categories such as new ice, first year ice, and multi-year ice).
3. Land-fast ice is crucial to the coastal processes. Thus, landfast ice models including scouring and anchoring processes should be developed. At the same time, parameterization of landfast ice is also necessary.
4. Discontinuous Lagrangian ice models such as granular models should be compared to the continuum models such as Eulerian models to find out the advantages and disadvantages.
5. As spatial scale becomes less than 10km, satellite observations show sea ice has strong anisotropic property, while most models used so far are isotropic. Thus, anisotropic models should be developed to better capture sea ice properties such as sea ice fractures, stresses, ridging, rafting, etc.
6. Coupled ocean-ice model should consider mixing of ocean tides and surface waves. The coupling of sea ice stress, convergence/divergence to the ocean should be taken into account. A turbulence closure model should be implemented in the ocean model.
7. Ocean model resolution has to be eddy resolving to resolve coastal eddies, upwelling/downwelling, dense water formation, the Arctic halocline ventilation.
8. For climate atmosphere-sea ice-ocean models with grid size larger than 10km, a parameterization of 10km processes for anisotropic is necessary.
9. Observation of landfast ice and deployment of the land-based CODAR.

APPENDIX A
BIOGRAPHICAL SKETCHES OF INVITED PARTICIPANTS

BIOGRAPHICAL SKETCHES OF WORKSHOP PARTICIPANTS

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APPENDIX B
LIST OF ATTENDEES

List of Workshop Attendees

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APPENDIX C
AGENDA

Final Agenda

Minerals Management Service (MMS) - Alaska Outer Continental Shelf (OCS) Region
Beaufort Sea Physical Oceanography Workshop

<u>Tuesday - 4 February 2003</u>

7:30 am	**Registration**
8:00 am	**Minerals Management Service Introduction** Cleve Cowles, Ph.D, Chief, Environmental Studies Section, MMS
8:15 am	**Physical Oceanography of the Beaufort Sea: An Overview** Tom Weingartner, Ph.D., Institute of Marine Sciences, University of Alaska Fairbanks (UAF)
8:45 am	**Exits and Entrances: Large-scale Arctic Ocean Circulation as a Neighbor for the Beaufort Sea** Rebecca Woodgate, Ph.D., Applied Physics Laboratory, University of Washington
9:15am	**The Joint Roles of Pacific and Atlantic-Origin Waters in the Canada Basin Halocline: Observations from 1997 Onwards.** Fiona McLaughlin, Ph.D., Institute of Ocean Sciences, Fisheries and Oceans, Canada
9:45 am	**Break**
10:00 am	**Observations and Modeling at a Regional Scale: Beaufort Gyre** Andrey Proshutinsky, Ph.D., Dept. of Physical Oceanography, Woods Hole Oceanographic Institution (WHOI)
10:30 am	**Sea Ice over the Beaufort Sea Shelf: Characteristics and Significance for Regional Geography** Hajo Eicken, Ph.D., Geophysical Institute, UAF
11:00 am	**Spreading Pathway of Eastern Chukchi Summer Water in the Western Arctic Ocean** Koji Shimada, Ph.D., Japan Marine Science and Technology Center (JAMSTEC)
11:30 am	**Lunch - Hosted by MBC *Applied Environmental Sciences***
12:30 pm	**Varieties of Temperature Minimum Water in the Western Arctic Ocean** Motoyo Itoh, Ph.D., JAMSTEC
1:00 pm	**The Sensitivity of Arctic Sea Ice to Oceanic Heat Flux** Humfrey Melling, Ph.D., Institute of Ocean Sciences, Fisheries and Oceans Canada
1:30 pm	**Shelfbreak Circulation in the Alaskan Beaufort Sea: Mean Structure and Variability** Robert Pickart, Ph.D., Dept. of Physical Oceanography, WHOI
1:45 pm	**Shelfbreak and Slope Processes in the Beaufort and Chukchi Seas** Ed Carmack, Ph.D., Institute of Ocean Sciences, Fisheries and Oceans Canada
2:15 pm	**Theoretical Considerations of Alongshelf Currents, Upwelling, and the Ice Edge** David C. Chapman, Ph.D., Dept. of Physical Oceanography, WHOI

2:45 pm Break

3:00 pm **Wind and Buoyancy Forced Motions on Shallow, Vertically Stratified, Inner Shelves**
Andreas Münchow, Ph.D., Graduate College of Marine Sciences, University of Delaware

3:30 pm **Nearshore Circulation on the Alaskan Beaufort Shelf**
Steve Okkonen, Ph.D., School of Fisheries and Ocean Sciences, UAF

4:00 pm **Geochemical Tracers of the Freshwater Component of Beaufort Sea Circulation**
Christopher K.H. Guay, Ph.D., Earth Sciences Division, Lawrence Berkeley National Laboratory

4:30 pm **The Workshop on Small-scale Sea Ice and Ocean Modeling for Nearshore Beaufort and Chukchi Seas**
Jia Wang, Ph.D., International Arctic Research Center-Frontier Research System for Global Change, UAF

5:00 pm **Adjourn**

Wednesday - 5 February 2003

9:00 am **Review Working Group Goals and Objectives**

9:30 am **Working Group Session**

10:30 am **Break**

10:45 am **Working Group Session**

12:30 pm **Lunch - on your own**

1:30 pm **Working Group Session**

3:15 pm **Break**

3:30 pm **Working Group Session**

5:00 pm **Adjourn**

Thursday - 6 February 2003

9:00 am **Discussion of Recommendations of Working Group**

10:30 am **Break**

10:15 am **Finalize Recommendations**

12:30 pm **Adjourn**

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil, and other mineral resources. The MMS **Royalty Management Program** meets its responsibilities by ensuring the efficient, timely, and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States, and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.