NORTH PACIFIC RESEARCH BOARD PROJECT FINAL REPORT

Evaluation of ocean circulation models for the Bering Sea and Aleutian Islands Region

NPRB Project 402 Final Report

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March 2006

Abstract

This project explored the present and future state of ocean circulation modeling and biological modeling of the Bering Sea and Aleutian Island (BSAI) region of the North Pacific. A workshop of BSAI researchers and managers was convened to focus on this topic, and a summary of its findings (including presentations by participants) has been posted on the web: http://halibut.ims.uaf.edu/SALMON/BSIAModelWorkshop.

Based on the proceedings of this workshop, we attempt to summarize:

1) the present state of knowledge concerning the BSAI and its recent changes

2) the various types of circulation models which could be applied to the BSAI, with some assessment of their strengths and weaknesses in accurately representing circulation, mixing and exchange due to the forcing mechanisms (winds, tides, ice formation, river runoff) and topographic features (coastline, shelf break, Aleutian Island passes);

3) existing physical and biological models of the Bering Sea;

4) the adequacy of present forcing and bathymetry datasets for use in models, and where they might be improved;

5) current status and future prospects for data assimilation into Bering Sea models;

6) the modeling needs of managers for this region;

7) a timetable over which we might expect the development of improved models of circulation and biology in the BSAI.

Key Words

Bering Sea, Aleutian Islands, Circulation modeling, Biological Modeling, Individual-Based Modeling

Citation

Hermann, A.J. and D.L. Musgrave. 2006. Evaluation of Ocean Circulation Models for the Bering Sea and Aleutian Island Regions. North Pacific Research Board Final Report 402, 51 pp.

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A. Study chronology

This project did not build directly on previously funded NPRB projects, but benefited from the expertise of many individuals supported by NPRB over the years.

B. Introduction

The ocean circulation of the highly productive Bering Sea-Aleutian Island region is exceedingly complex, with energetic phenomena over a broad range of space and time

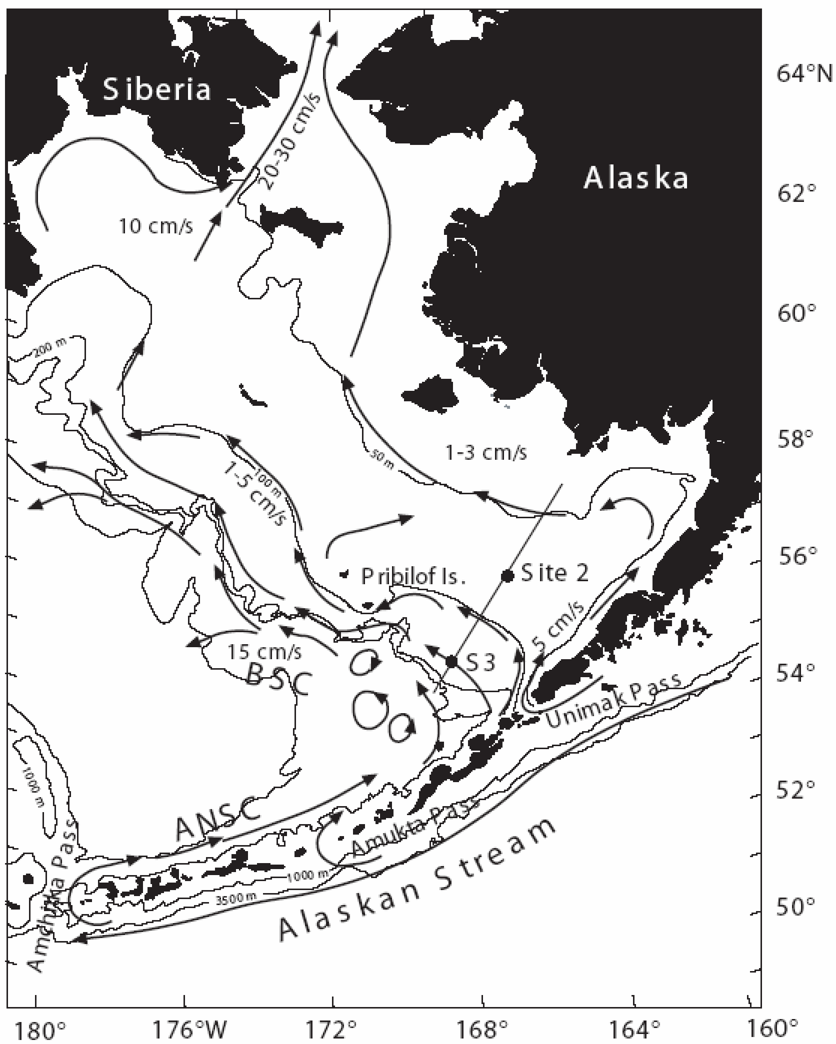

Fig. 1 Place names and schematic of mean circulation in the southeastern Bering Sea. ANSC = Aleutian North Slope Current; BSC = Bering Slope Current. Positions of continuous hydrographic mooring sites 2 and 3, and a cross-shelf hydrographic section, are noted. Modified from Stabeno et al. (1999).

scales. Such energetic phenomena include: tidal mixing, alongshelf flows, shelf-slope exchange through canyons, mesoscale (150km) eddies, flows through passes, and the yearly formation, drift, and melting of ice. All of these phenomena may interact with each other. For example, tidal and subtidal flows are not cleanly separable as tidal mixing alters the density field, which affects the subtidal field through geostrophy. An overview of the eastern Bering Sea with major currents is shown in Fig. 1. This wide range of phenomena presents difficult challenges for both physical and biological models of the Bering Sea, whether such models are used for pure scientific insight or direct management of commercially important fish stocks. At the same time, dramatic changes are occurring in this complex system due to interannual variation and long-term climate shift. A summary of the various types of physical and biological models which could be applied to the Bering Sea, detailing their promise and their pitfalls, was deemed timely.

C. Objectives

A workshop was convened in early February, 2005, for the purpose of evaluating the present and future state of ocean circulation modeling for the Bering Sea and Aleutian Island (BSAI) region of the North Pacific. The workshop was funded by the North Pacific Research Board, and was led by Drs. A. J. Hermann and D. L. Musgrave. The workshop was structured to include presentations by experts on the extant types of ocean circulation models (OCMs) and related biological models, the state-of-the-art in data-assimilation into models, and the application of the models and data-assimilation schemes to the BSAI region. While the initial objective of the project was to focus primarily on circulation models, it became increasingly apparent that biological models should be discussed in some detail as well. Hence the workshop attendees ultimately included researchers/managers from both fields.

D. Methods

The workshop took place over two days. The first day consisted of presentations by representatives of groups that have:

- Simulated circulation in the BSAI region.
- Observed and analyzed the relevant oceanographic and atmospheric structures and process in the BSAI region.
- Observed and analyzed the various forcing mechanisms in the BSAI region.
- Managed resources within the BSAI region.
- Developed or used the different vertical coordinate systems available for 3D circulation models.
- Developed or used structured vs. unstructured grids (finite-difference as well as finite-volume) in circulation models.
- Developed or used ice models.
- Developed or used data-assimilation methods in OCMs.
- Developed or used lower trophic level ecosystem models, or individual based models for higher trophic levels (e.g. fish).

Subsequent to these talks, two working groups were tasked to discuss: 1) needs for improved circulation models of the BSAI; 2) what types of circulation and biological models would best fit the needs of resource managers. On the second day of the workshop, the group collectively discussed the pathway for development of improved models, and their migration to useful products for resource managers and other users.

Based on the proceedings of this workshop, we attempt to summarize:

1) the present state of knowledge concerning the BSAI and its recent changes

2) the various types of circulation models which could be applied to the BSAI, with some assessment of their strengths and weaknesses in accurately representing circulation, mixing and exchange due to the forcing mechanisms (winds, tides, ice formation, river runoff) and topographic features (coastline, shelf break, Aleutian Island passes);

3) existing physical and biological models of the Bering Sea;

4) the adequacy of present forcing and bathymetry datasets for use in models, and where they might be improved;

5) current status and future prospects for data assimilation into Bering Sea models;

6) the needs of managers;

7) a timetable over which we might expect the development of improved models of circulation and biology in the BSAI.

This summary represents a compilation of: presentations given by the participants; extended abstracts submitted by the participants; notes from discussion groups; personal views of the authors. The final agenda, list of participants, and extended abstracts received are shown in the Appendix. An official website was created for the conference (http://halibut.ims.uaf.edu/SALMON/BSIAModelWorkshop/), and contains presentations contributed by participants.

E. Summary of Workshop Findings

E.1. Present state of knowledge of the BSAI region

The Bering Sea covers over 2 million square km of the northernmost region of the Pacific Ocean. Its borders are defined to the north by Alaska, the Bering Strait, and northeastern Siberia, and to the south by the arc of the Alaska Peninsula, Aleutian Islands, and Commander Islands. The bathymetry of the Bering Sea can be divided into two primary regions: a shelf region (less than 150m deep) to the northeast, and a deeper plain (3,700 - 4,000m deep) to the southwest. In the west the Aleutian archipelago extends to the Komandorskiye Islands which are geologically part of the Aleutians. Other major islands included in the area are the St. Lawrence and Nunivak Islands (which are the largest in the Bering Sea), the Pribilofs (Fur Seal Islands), St. Matthew, Nelson, and Karagin

Islands. The Bering Sea includes several marginal bodies of water including the Gulf of Anadyr, Norton Sound, and Bristol Bay. The Bering and Chukchi Seas are connected via the Bering Strait which is only 85 km wide at its narrowest breadth and 50 m deep.

The Aleutian Island region constitutes the southern boundary of the Bering Sea. A summary of prominent circulation features in the Bering Sea, including the Aleutian Islands, can be found in Stabeno et al. (1999); flow through the passes is described in detail in Stabeno et al. (2005). Major passes between the islands, which connect the North Pacific with the Bering Sea, include Unimak, Tanaga, Amukta, and Amchitka passes, Near Strait, and Blizhny Strait. Flows through the passes transport water (and materials) both into and out of both the shelf region and the deeper plain, with a net inflow overall. The Aleutian passes are very narrow (most less than 50km deep) and the energetic spatial scales of their currents are even smaller, as there are frequently opposing flows in their eastern and western halves. The Alaskan Stream flows along the southern boundary of the Aleutian Islands, and penetrates the Bering Sea with a distinctive water mass signature. Net inflow through Aleutian passes (and the western Straits) is balanced by net outflow through the Bering Strait into the Chukchi Sea. Ice forms seasonally in the Bering Sea and has a great influence on the currents and water properties.

Flow through the Aleutian Passes is highly variable in space (i.e. among the different passes) and in time. Seguam Pass is well mixed through June/July, with stratification observed later in the year. The strength of the Alaskan Stream affects its position, which in turn governs the flow through the passes. Amukta Pass has ~4 Sv of flow; the eastern passes together make up ~5 Sv total flux into the Bering Sea. There is a net cooling of water in the Bering Sea, and flow through the passes hence supply significant heat (and a marked SST signal) to the region. Weak flow through the passes was observed in 1992, leading to speculation that the Alaskan Stream may have been further offshore than usual in that year. There is a tight relation between salinity and nutrients at depth. Many drogued drifters (over 300) have been released and tracked in the Bering Sea, allowing for summary maps of circulation in the region.

Ice-edge plankton blooms are observed on the SE Bering Sea shelf when ice persists beyond mid-March; without ice, there is no bloom until May-June, when stratification first develops. The so-called "Oscillating Control Hypothesis" for the Bering Sea (Hunt et al., 2002) posits that an early (Jan-Feb) ice retreat leads to large copepods, and feeds a pelagic food web. Conversely, a later ice retreat results in small copepods, and feeds a benthic food web. Evidence from recent years (Stabeno et al., 2006) suggests that a persistent warming trend is shifting more of the Bering Sea towards early ice retreat, and hence a pelagic food web. Unusual blooms of coccolithophores in the past decade have also been noted (Vance et al., 1998).

There are several distinct spatial regimes on the gently sloping Bering Sea shelf, corresponding to depth range (Schumacher and Stabeno, 1998). Generally speaking, the different hydrographies observed in these regimes are the result of competition between tidal mixing (which reduces stratification) and heating (which increases stratification). The innermost shelf (0-50m) is uniformly mixed, the middle shelf (50-100m) is a two-layer system, and the outer shelf (100-1000m) typically exhibits mixed surface and bottom boundary layers with continuous stratification in between. The shelf break is a persistent region of high production (the "Green Belt" noted by Springer et al., 1996)

Ice has been retreating overall in the Bering Sea; it appears the region has warmed by over 3 degrees C over the past decade (Stabeno et al., 2006). While the incidence of relatively cold winters has been decreasing in frequency, as apparent in time series of seasonal ice cover, a secular warming is especially apparent in summer. For example, each of the summers of 2002 through 2004 featured vertically integrated heat contents greater than any previously recorded. Part of this recent warmth can be attributed to the recent overall sense of the Arctic Oscillation or AO (Thompson and Wallace 1998). Unlike the Eurasian sector of the Arctic, the Bering Sea and Alaska tend to be cooler than normal when the AO is in a positive state. This effect is due to the AO's influence on sea level pressure in the vicinity of the Aleutian low, and ultimately, the favoring of cyclones with warm, maritime origins versus anticyclones of cold, arctic or continental origins. The AO has tended to be in a neutral to negative state since about 1996, thereby promoting warm winters, reduced sea ice, earlier onsets of spring, and finally, warmer ocean temperatures in summer. The role of ocean circulation dynamics in the trends seen in the Bering Sea has not yet been determined.

The Pacific Decadal Oscillation or PDO (Mantua et al. 1997) has been identified as the dominant spatial EOF of wintertime SST anomalies in the North Pacific. There is increasing appreciation that this mode does not fully describe important aspects of the North Pacific atmosphere-ocean climate system. The shift in the PDO in 1976-77 did represent the most systematic transition in the North Pacific climate and marine ecosystem of the last half century. But for the period from the early 1990s to 2002, the second mode (based on EOF analysis) has dominated North Pacific variability. Notably, the state of this mode from 1998 through 2002 supported atmospheric forcing of an anomalously strong sub-arctic gyre in the North Pacific. At present, the state of the wintertime North Pacific is characterized by weak and inconsistent signals in both of its two leading modes. Moreover, clear indications of the current trajectory of the North Pacific climate system is lacking. Greater attention is starting to be paid to the North Pacific climate system during the warm season. The PDO does have a substantial expression at this time of year, but the second mode of variability is much different than that during the cold season. It consists of a pattern with the amplitude of SST anomalies increasing poleward; its existence appears to reflect a warming trend over the last 4 decades for the region stretching from the Aleutians to the northern Gulf of Alaska. The linkages between the summertime state of the North Pacific atmosphere-ocean and the marine ecosystem are only beginning to be explored.

E.2. Classes of Ocean Circulation Models

Ocean circulation models (OCMs) have recently achieved an impressive level of sophistication. Important new capabilities include: generalized vertical coordinate systems allowing more effective transition across the deep/coastal ocean boundary; well developed sub-models for the evolution of coupled biological and geochemical tracers; robust procedures for one-way nesting of models with differing spatial windows and resolution; efficient algorithms for multi-variate data assimilation; and pre-operational prediction systems for global, regional and local areas. Over the next five years, further progress is anticipated, including the refinement of operational forecast and analysis systems for the North Atlantic and other regions, the emergence of powerful alternatives for multi-scale ocean modeling including adaptive unstructured grid techniques, and the availability of new approaches for interdisciplinary modeling and data assimilation.

Despite this success, the large extent of the BSAI region, the interaction of the shelf with basin waters, ice formation, open ocean boundary conditions, a large range of relevant spatial scales (e.g. flows through narrow passes), complicated coastline topology, numerous marginal bodies of water, and extreme ranges of wind and buoyancy forcing present daunting challenges for any OCM; each will have advantages and disadvantages for handling these disparate elements.

Broad categories of OCMs include pure tidal models, quasi-geostrophic (or other reduced physics) models, and primitive equation models. The latter category includes most terms of the full equations of motion, but typically assumes nearly hydrostatic conditions so that the vertical velocities may be calculated diagnostically. Presently there are three general categories of primitive equation circulation models, according to the vertical coordinate system used: 1) *terrain-following coordinate*, 2) *z-coordinate* and 3) *layered coordinate*. The terrain-following and z-coordinate classes can incorporate any of several standard vertical mixing schemes (e.g. KPP [Large et al., 1994], Mellor and Yamada [1982], PWP [Price et al, 1986]). Each vertical class can be implemented in several different horizontal coordinate systems (rectilinear, curvilinear-orthogonal, or unstructured). Note that hybrid approaches also exist, which apply different coordinate systems in different locations (e.g. Bleck, 2002; Chassignet et al., 2003).

1) *Terrain-following models* (e.g. POM [Blumberg and Mellor, 1997]; SPEM [Haidvogel et al, 1991]; ROMS [Haidvogel et al., 2000; Shchepetkin and McWilliams, 2004]) utilize a constant number of vertical gridpoints at all horizontal locations; these points span from the bottom of the ocean to the instantaneous height of the free surface. Vertical spacing

may be adjusted for enhanced resolution of the surface and bottom boundary layers. Advantages include the efficient coverage of complex bathymetry and boundary layers with a small number of gridpoints. Disadvantages include the difficulty of separating horizontal from vertical pressure gradients, as the native coordinate system is typically oblique to the geopotential surface. Some smoothing of bottom topography is typically required for numerical stability.

2) *Z-coordinate models* (e.g. MOM [Pacanowski and Griffies, 1998]; Adcroft et al. 1997) utilize gridpoints fixed in space at constant depths, which do not vary among horizontal locations. This makes it easier to compute accurate horizontal pressure gradients than in the terrain following system, but much harder to represent complex bathymetry and bottom boundary layers. A modern variant of this approach represents the bottom grid element as a "shaved cell" (a triangular, rather than rectangular, box; Adcroft et al. 1997).

3) *Layered models* (e.g. MICOM [Bleck and Boudra, 1981]) keep track of the depth and thickness of pre-defined density layers, as they undulate through time. While this approach avoids the drift of isopycnal layers due to the excessive interior mixing found in other models, it is usually difficult to deploy this system cleanly near complex coastal bathymetry, where density surfaces obliquely intersect topography. The spatially variable vertical mixing of coastal areas (esp. that due to tides) is likewise problematic for such models.

4) *Unstructured grids* (e.g. SEOM [Haidvogel et al., 1997]; FVCOM [Chen et al., 2002]; ADCIRC [Zhang et al. 2004]) allow more arbitrary placement of grid elements, and hence spatially variable grid resolution. The Bering Sea includes a large dynamic range in lateral spatial scales. This is difficult for a single structured-grid OCM to accommodate; the smallest required spatial scale largely dictates the resolution of the model, thus increasing the computational effort in regions where the scales are much greater. This fact has limited the application of curvilinear structured grids in some regional studies. Nested grids of increasing higher resolution can be used for economy in such cases, and have been deployed with much success in other regional ocean studies. As an alternative,

unstructured grids can accommodate very complicated coastline topology and flexibly adjust their lateral resolution to accommodate observed or expected oceanographic features, such as fronts. Such codes can be implemented with spatially variable time steps, to reduce the computational overhead. Although these OCMs are less well tested, and typically more difficult to implement than the more conventional structured grid models, they hold some promise for the BSAI region. The experience of Baptista et al. (2005) suggests that these models are quite successful at resolving plumes, fronts, and the Lagrangian paths along them at estuarine outlows.

E.3. Existing physical and biological models

E.3.1 Atmospheric models

Two primary sources of atmospheric hindcasts for driving oceanic models are the National Center for Environmental Prediction (NCEP) and European Center for Medium Range Weather Forecasting (ECMWF) reanalyses. These hindcasts are based on global, data-assimilating atmospheric models. NCEP products are freely available online for the period 1930-present. Other atmospheric reanalysis projects include EPTOMS (at large scale), ETA (at regional scales), and the North American Regional Reanalysis (NARR) project. NARR hindcasts cover the North American continent including Bering Sea at 32 km resolution, for the period 1979-2004. In addition, many climate projections from coupled climate models are presently online, for use by ocean modelers in testing climate scenarios. For example, atmospheric hindcasts, climate projections, and idealized coupled air-sea simulations are being produced under the Community Climate System Model (CCSM) program.

E.3.2. Ice models

The Hibler (1979) model and its descendants have been popular choices for ice modeling. All ice models contain a thermodynamic component (the surface energy balance), a dynamical component (momentum balance), and a conservation component (formation and melting). For the dynamical component, the Hibler model treats ice as a viscous-plastic solid. Ice models vary in the number of layers (snow/ice/water) they consider, and the number of categories of ice (first year, second year, frazil, etc) which are considered.

E.3.3 Circulation models

At least four models which include the Bering Sea at eddy-resolving scales are currently in use by various research groups. Those with ice utilize dynamics based on the Hibler (1979) algorithms, with modifications and enhancements appropriate to their numerics and atmospheric forcing.

1.) W. Maslowski and colleagues have examined the output from a model of the Northern Hemisphere (north of 30 degrees N) at 9 km resolution, based on the z-coordinate Parallel Ocean Program (POP) model. POP utilizes the z-coordinate and the CICE ice model. This model includes flows through the Aleutian passes. Surface values of salinity and temperature are relaxed toward a monthly climatology. No tides were included in these simulations. For details of this model, see the extended abstract appended to this report.

2.) Y. Chao and colleagues have executed multidecadal hindcasts with a 12.5 km resolution model of the full North Pacific, based on the terrain-following Regional Ocean Modeling System (ROMS). At the time of this workshop, the simulation did not include tides or ice.

3.) J. Wang and H. Hu have constructed a regional model of the Bering Sea at 15' x 10' resolution (CIOM, based on the Princeton Ocean Model; POM). POM uses a stretched vertical coordinate, here with 24 vertical levels. Wang and Hu's implementation includes ice, mixing by tides, and mixing by surface wind waves.

4.) E. Curchitser, A. Hermann and colleagues have constructed a 10 km resolution model of the Northeast Pacific and the Bering Sea (NEP domain) with 42 vertical levels. This model is one component of a spatially nested suite of models developed under Global Ecosystem Dynamics (GLOBEC) support (Curchitser et al, 2005; for model details see http://www.pmel.noaa.gov/~dobbins/cgoa.html). Like Chao's model, this suite is based on ROMS, but includes a three-layer ice module (Budgell, 2005). An exended hindcast of 1950-present is underway; tides will ultimately be included in this effort. An earlier, 4-km resolution model with tides was reported in Hermann et al. (2002).

Table 1. Bering Sea ocean circulation models

Ocean Model	Associated Ice Model	Dimension	Resolution
ROMS (GLOBEC and JPL)	Budgell	3D	~10km
CIOM	Hibler (multi-category)	3D	~10km
POP	CICE	3D	~9km

E.3.4. NPZ Models

E.3.4.1. 1D models

The North Pacific Ecosystem Undersea Reigional Ocean (NEMURO) model, a 1D (water column) ecosystem model developed under the auspices of the PICES Model Task Team, has been implemented in the Bering Sea by B. Megrey and collaborators. NEMURO includes nitrogen and silica, as well as two size classes of phytoplankton and zooplankton, and both dissolved and particulate organic matter. Iron is not presently included. A version of this model has been developed which includes saury and herring as top predators in the NPZ system. These models have yielded realistic results when coupled with spawner/recruit functions. Merico et al. (2004) have developed a two-layer water column model of phytoplankton succession for the Bering Sea, and attempted to model the appearance of the coccolithophore bloom in recent years.

E.3.4.2. 3D models

There are few groups developing 3D NPZ models in the BSAI region. J. Wang and C. Diehl of the Arctic group at UAF have developed a 3D NPZ model for the Bering Sea, which runs with the CIOM model noted above. Y. Chao, F. Chai and collaborators have added an NPZ component to their North Pacific model. Hermann and collaborators have initiated a simple NPZD model on the Northeast Pacific grid of their nested GLOBEC models. There are also some global climate/ocean models that include NPZ models, but these are highly biologically aggregated, basin scale models which use large grid resolutions, and are not very detailed in regions such as the BSAI.

NPZ models have been run both “online” as a subroutine of a circulation model, and “offline” (for economy) using pre-stored, time-filtered circulation model output. Offline usage can introduce some artifacts, e.g. less accurate treatment of tidal dispersion as tides are filtered out in the pre-stored file.

S. Hinckley, A. Hermann and colleagues have developed an 11-compartment 3D NPZ model for the Gulf of Alaska (GOA) under the GLOBEC Northeast Pacific program, which has been implemented on multiple grids of the physical ROMS model. When run on the 10 km Northeast Pacific (NEP) grid, this model has included the Bering Sea. Presently this model consists of 11 compartments. Iron was included to allow the simultaneous modelling of deep oceanic areas (the subarctic gyre, a Hign Nutrient Low Chlorophyll ecosystem) and the coastal ocean. Some changes to model compartments would be needed to adapt this NPZ model to the Bering Sea ecosystem. These might include parameterization of the euphausiid compartment for *Thysanoessa*, spp. instead of *Euphausia pacifica*, the addition of *Calanus marshallae,* and the inclusion of low-temperature Q10s and other rates affected by the lower temperatures of the region.

Hinckley, Hermann et al. have also developed a 3D NPZ model specifically designed to provide a spatially and temporally dynamic prey field for young walleye pollock modelled with an Individual-Based Model (IBM, see below). This NPZ model was designed for the Shelikof Strait and western GOA region. It includes compartments for nitrogen, phytoplankton, *Neocalanus*, spp. (as the biomass dominant grazer) and 13 stages of *Pseudocalanus*, spp. which provide the food source for young pollock larvae. This model could also be reparameterized for the Bering Sea, and run within the ROMS model, however, there are no present plans to do so.

Table 2. NPZ Models

NPZ Model/ (Circulation Model)	Dimension	Additional Info
(CIOM)	3D	
(ROMS)	3D	JPL/UCLA/Chai, GLOBEC
NEMURO	1D	Not 3D in Bering Sea Yet
(POP)	3D	Walsh

E.3.5 Individual-based Models

Individual-Based Models (IBMs) are constructed for many different purposes. When coupled with 3D ocean models, they are uniquely suited for the examination of problems related to transport of planktonic organisms, which may be tracked in a Lagrangian manner in coupled IBM/hydrodynamic models; and for the examination of mechanisms and processes affecting individuals which might be lost in an aggregated population or Eulerian model. It is possible to include complex behaviors and interactions between individuals where these are known or thought to be important. Truly realistic IBMs require large amounts of data on processes, rates and behaviors and their physical driving functions. For many species, this information is not available. Although float tracking without biology in 3D physical models can yield important information, IBMs also usually have bioenergetics and behavioral mechanisms included that are specific to the species under investigation. Most commonly, at least in marine systems, IBMs have been constructed to study: plankton transport, bioenergetics and behavior; fish recruitment; egg, larval and juvenile transport and bioenergetics and behavior; and adult fish migration and bioenergetics. The last can be very difficult, as parameterizations of movement, migration and schooling behavior may be needed and information on these is often sparse.

Hinckley, Hermann and colleagues have built IBMs of walleye pollock early life stages (from the spawning of eggs, through larval and 0-age juveniles in the fall) for both the western Gulf of Alaska and the Bering Sea. The GOA pollock IBM has been coupled with the SPEM hydrodynamic model and the NPZ model described above, and used to study recruitment variability in this stock. A study is presently underway with this model to develop a pre-recruit index from the model that may be useful to management. The Bering Sea pollock IBM was developed under the auspices of the South East Bering Sea Carrying Capacity program, however the physical model available at the time was constructed for other purposes, and did not have the correct domain to utilize with the pollock IBM for the study of recruitment in this region. Interest has been expressed in developing IBMs for crab, winter spawning flatfish and euphausiids in the BSAI, however this will be dependent of data availability and funding.

As with NPZ models, IBMs can be run as an integral part of a circulation model, or "offline" with pre-stored circulation and NPZ output. The latter introduces some bias, but is more economical and hence allows for more sensitivity experiments to be run with the IBM.

Table 3. IBM Models

Species	Model/Modeler	Dimension	Notes
Pollock	SPEM – Hinckley	3D	Eggs through juveniles
Pink salmon	OSCURS – Rand	2D	
Mechanics	ROMS – Dobbins	3D	Diurnal vertical migration
Pollock	John Horn	3D	Adults only, not tied to physics

Stellar Sea Lions	John Horn	3D	
Saury, Herring	NEMURO - Megrey	1D	Quasi-IBM

E.3.6 Aggregated models

One class of model encompasses the entire food web, but in a spatially aggregated fashion. The model templates ECOPATH and ECOSIM have been popular for this work. The former takes existing information regarding biomass and feeding of each species or group of species, makes standard ecological assumptions about missing flows among the components (e.g. regarding standard respiration and feeding rates), and yields the best guess of steady-state fluxes through the entire ecosystem. ECOSIM is similar to ECOPATH, but biomasses and the fluxes between them are allowed to evolve through time. A coarse level of spatial aggregation is typically used (e.g. the entire Bering Sea), with diet varying in space. Such models are driven by external climate using averages and past climate distributions. K. Aydin, J. Horn, and collaborators have constructed ECOSIM-based summaries of the Bering Sea and the Aleutian Islands, and have looked at intrinsic variations in the food web driven by white noise at the lowest trophic level. They have also driven ECOSIM with NEMURO results, and compared the secondary production between these two models (Aydin et al, 2005). ECOSIM was found to have less variation in secondary production, because of the impact of grazing by higher trophic levels not included in NEMURO. A proper delineation of the mixed layer depth was crucial for getting reasonable results from the coupled system.

E.3.7 Fisheries models

A popular class of models used by fisheries managers is Multi-Species Virtual Population Analysis. This technique uses existing catch data, along with assumptions about natural mortality and feeding, to construct time series of population levels for multiple species; in this sense it is similar to the ECOPATH approach. P. Livingston and colleagues have used this approach to track population levels in the Bering Sea.

E.4. Adequacy of models, forcing and bathymetry

E.4.1 Numerics and resolution

It may be impossible to devise a truly objective test of one model versus another, as the different models inevitably use different forcing and bathymetry. That being said, desirable features for multiscale ocean modeling could include: arbitrary vertical coordinates (layered in some places, level vertical coordinates in others); multiple spatial scales to resolve important fine-scale features; accurate and converegent algorithms; local and global conservation of tracers; non-oscillatory numerics; adaptive space-time resolution; efficient scalability on multiple processors; coupled sub-models for turbulence, sediment, and sea ice. Note that any model needs to be capable of dealing with strong advection in the presence of tides. As noted earlier all present classes of models have deficiencies, which include: 1) terrain-following coordinates require smoothed bathymetry for accurate pressure gradients, and tend to overly enhance bathymetric steering; 2) z-coodinate models are not numerically convergent, and have limited resolution of bottom boundary layers over sloping bathymetry; 3) layered models cannot be used in coastal areas with strong tidal mixing; 4) unstructured grids are difficult to implement and stabilize.

The Aleutian Passes require the highest resolution in the BSAI. Flows in this area exhibit fine spatial structure as tidal and subtidal dynamics interact with narrow and shallow passages. Proper flux through the passes is crucial for setting the conditions in the Southern Bering Sea; cross-shelf exchange must be better represented for that area, as well. There was a strong sense among the workshop participants that a high-resolution model of the passes would benefit the entire modeling enterprise for the BSAI, if a way could be found to successfully nest this with the larger domain. One approach would include a spatial hierarchy of: a) North Pacific/Global; b) Bering Sea; and c) Island/Pass models. Two-way feedback with the nested grids might be required for this effort to be successful. Another possible approach entails unstructured horizontal grids for the entire Bering Sea, but these need further demonstration.

Vertical resolution is highly important in the Bering Sea, given the importance of tidal mixing, summer heating, and ice-edge stratification. Multiyear hindcasts of the BSAI region ought to have resolution of 1-5 m in the surface mixed layer and the bottom boundary layer on the shelf, to accurately capture the physics there.

E.4.2 Ice

An accurate ice model is essential for addressing changes in ice edge blooms and the related Oscillating Control Hypothesis. For ice per se, the Bering Sea can be considered as an isolated basin. The first order problem here is the location of the ice edge, which is set by the balance between ice advection out from the coast and from the north, and ocean heat advection in towards the coast and from the south. Ice forms annually in the Bering Sea in the north and near the coast, is advected into deeper and southern areas, and is completely melted in the summer. These are simple dynamics as compared to higher latitudes, where multiyear ice classes must be considered. In particular, a sophisticated treatment of the stress and strain of a multiyear ice field is not required for the Bering Sea. It was concluded that a simple, multilayer ice model (which allows for both snow and ice) with ice treated as a viscous-plastic solid (as in the Hibler formulation), is adequate for this region. Major uncertainties in many ice models derive from the wind forcing and ocean heat transport; in the Bering Sea, we have found that the ice edge is very sensitive to the magnitude of the shortwave radiation forcing. Hence, more accurate ice dynamics are largely dependent on accurate atmospheric forcing in the Bering Sea.

E.4.3 Atmospheric forcing

Hindcast atmospheric fields from the NCEP reanalysis have strengths and weaknesses. The wind fields from NCEP are probably reasonable at the 2-degree scales resolved. Most of the southern Bering Sea does not respond to fine-scale wind variations (with the notable exception of the Aleutians, with their associated high mountains and narrow passes). The Northern Bering Sea contains a more stratified atmosphere; here land topography becomes more significant in setting the winds. The strength of two-way, mesoscale air-sea interaction in the Bering Sea is an open question.

Despite the usefulness of NCEP winds, there are systematic errors in an important component of the net heat fluxes at the air-sea interface. Specifically, there is considerable evidence (Ladd and Bond 2002) for underestimation of low cloud coverage and hence overestimation of insolation during the warm season. This error is partly offset by a concomitant error of the opposite sense in the downward longwave radiative flux. The problem is more pronounced during high pressure, fair-weather conditions. Users of the NCEP Reanalysis (it is unknown whether the ERA-40 product from ECMWF includes a similar bias) may have to apply ad-hoc corrections to avoid unrealistic heating by as much as 70 W/m^2 in the BSAI region. Improved algorithms are needed to correct for this deficiency, e.g. those based on observed clouds, such as the CCSM hindcast reanalysis. There are new efforts underway to improve the NCEP product, but the timetable for this is uncertain. Improvements to bulk flux formulae, used to translate atmospheric properties into flux of heat and momentum into the ocean, are improving their accuracy in high latitude situations.

Extended range atmospheric forcing would certainly be useful for ocean model experiments, but is difficult to do well. Presently we need to rely on seasonal forecasts and scenarios, due to inherent predictability limits of atmospheric details. Certain gross features of the atmosphere, such as mean global temperature, are probably more predictable than any of the details of local climate. Global climate downscaling is an active, and likely fruitful, field of study.

E.4.4 Freshwater discharge

Freshwater discharge had been gauged for a few rivers which flow into the Bering Sea, but these measurements have unfortunately been discontinued by USGS.

E.4.5 Tides

Tidal flows in the Bering Sea include residual flows around islands (including those which bracket the Aleutian Passes). Existing circulation models can handle both subtidal and tidal flows together; this is necessary as the two inteact strongly in the Bering Sea. Tidal mixing affects the density stratification, which in turn leads to subtidal flows, and affects the yearly formation of ice. Regional models of the Bering Sea have exhibited realistic tidal flows when driven by lateral boundaries alone; a local body force was not required at the scale of this basin. Accurate tides are crucial in setting the multiple biophysical zones across the Bering Sea shelf.

The phasing of tidal components is significant because these interact nonlinearly and modulate vertical mixing at tidal and subtidal frequencies. The phasing of diurnal signals (and hence the time of day when mixing is strongest) may have important biological ramifications.

E.4.6 Bathymetry

Bathymetric datasets in the Bering will need improvement for high-resolution modeling, and are especially poor in the Western Bering Sea. Bathymetry of the Aleutian passes is marginally resolved, although recent hydrographic lines have improved our knowledge. Better datasets are probably on the horizon as USGS eventually digitizes all of its charts.

E.4.7 NPZ models

Ideally, NZP models of the BSAI region would replicate ice-edge and normal spring blooms, the frontal structures and differences in communities by domain (e.g. the benthic ecosystem of the inner-middle shelf and the pelagic ecosystem of the outer shelf, slope and basin), the Green Belt, and the broad north-south gradient in benthic vs. pelagic communities. One might want to include coccolithophores, or important prey for fish, seabirds or marine mammals, if the purpose of the model was to couple with an IBM. Diapause of large oceanic copepods, and the transport of these and other ecosystem components on and off the shelf may also be important to the questions being asked. Compartments for the benthos, detritus, small and large phytoplankton, small and large microzooplankton, and large oceanic copepods would be of use, and perhaps *Calanus marshallae*, *Acartia*, and/or *Pseudocalanus*, spp., and one or more euphausiids. One might want to include jellyfish, as they are a ubiquitous part of the Bering Sea ecosystem in summer. A compartment for iron may be necessary, if HNLC conditions are present in the deeper waters. It may be necessary to model silicate as well.

E.4.8 IBM models

Better information on fish movement and behavior are needed; perhaps these can only be derived from laboratory studies. Better information on the distribution of fish is also required. IBMs can benefit from quantities such as turbulence, saved from circulation model runs, as these affect individual behaviors and foraging success.

E.4.9 Aggregated models

ECOPATH and ECOSIM could benefit from suitably aggregated physical and NPZ model output, for use in more spatially explicit (that is, less spatially aggregated) simulations. Such models could be run with multiple spatial domains, where the flux of water and nutrients among domains is specified as an external forcing function derived from the circulation and NPZ models. An interesting question exists as to whether such aggregation should be set up according to fixed space, or according to water mass or biological regime type.

E.4.10 Fisheries models

As with the "aggregated models", these could be made spatially explicit (provided the data is available), for improved forecasts. Models which deal with multiple life stages are desirable, as well.

E.4.11 Model coupling

Putting this all together, the "ideal" biological model might include multiple species and multiple life stage components, with specific species treated using spatially explicit IBMs, coupled to multi-compartment NPZ and physical models, all running simultaneously on the same spatial grid and with the same time step. Proper feedback among the different components would be one of the major challenges, especially between IBM and NPZ components. More collaborative development of these types of models is recommended, as they will require substantial human resources. One way to ease the development of such multi-investigator models is to provide easy access to model output through web-based software such as the Live Access Server (for an example see http://ferret.pmel.noaa.gov/FOCI/servlets/dataset) New software and standards for coupling models will likely become more important over time.

For all models, longer time scales are needed than are presently simulated, to aid in ecosystem-based management (see below). New modeling efforts should be coordinated with the ongoing efforts of GLOBEC and related programs, where possible.

E.5. Status, Needs and Prospects for Data Assimilation

Data assimilating nowcasts/forecasts could yield substantial benefits in the Bering Sea. Note in particular that flows of water, T, S, and nutrients through the Aleutian Passes, if properly monitored, would serve as a powerful constraint on circulation in the Bering Sea. It is important to learn from existing examples of data assimilation, e.g. ONR, HICOM, and PWS efforts. Skill assessment is difficult to do well, and perhaps best learned by experience.

Several existing ocean models contain provision for data assimilation. Chao and colleagues have developed a 3D variational data assimilation code using ROMS (3DVAR) which has very low computational overhead. Wang et al have implemented a data assimilation algorithm into their Bering Sea model. More generally, Moore et al. (2004) have developed 4D variational data assimilation and related codes for use in ROMS. These include Tangent Linear, Representer, and Adjoint codes. The tangent linear version of ROMS is used to derive a cost function gradient for use by optimization schemes, and is also used in eigenfunction analysis to find the most rapidly growing perturbations. This information can be quite useful in determining where assimilated mooring data would be of greatest benefit in constraining model trajectories. In "strong constraint" 4DVAR, the Adjoint code proceeds forwards and backwards along the tangent linear trajectories, in order to optimize model forcing and parameters with respect to observed data. This contrasts with "weak constraint" 4DVAR, where observations are combined directly with data (e.g. "nudging" of model results to data). Areas where these codes have been implemented include the Southern California Bight, the US East Coast, the Gulf of Maine, the East Australian Current, and the Oregon Coast. The overhead for adjoint-based optimization can be substantial; for the tangent-linear adjoint, optimization takes approximately 5x the computational overhead of a single forward run.

Opitimization (essentially, data assimilation) schemes have been used for tuning of parameters in the NEMURO and other NPZ models. These include the adjoint approach noted above, as well as schemes based on genetic algorithms.

There is little in situ data to assimilate from the Bering Sea. Altimeter data exist for SSH and passive microwave satellite data exist for ice (based on the Scanning Multichannel Microwave Radiometer; SMMR). The usefulness of altimeter data for SSH is limited by the strong tides of the shelf. Historical XBT data is very sparse prior to the 70s. Hydrogrpahic and mooring data are especially lacking from the Western Bering Sea.

Stabeno's moorings (see Fig. 1) have provided some of the longest depth-resolving time series in the region. The BASIS program has been producing regular transects of hydrographic data in the Bering Sea in recent years.

Despite their limited spatial coverage, existing moorings on the shelf could yield improved hindcasts and nowcasts from models, because of their extensive correlation scales. The Bering Sea shelf is largely a two-dimensional system, with high correlation of density and velocity along isobaths when ice is not present.

Several global, data assimilating ocean circulation products exist but are probably of limited value at the finer regional scales of the Bering Sea. They may be useful as boundary conditions on regional Bering Sea models, however.

The atmospheric structure in the BSAI region over the last 5-6 decades can be described using reanalysis products from centers such as NCEP, but there are issues regarding these reanalysis products in the forcing of ocean numerical models. One of these issues relates to how air-sea interactions constrain surface thermodynamic fields in reanalyses. The near surface atmosphere in these products is generally in near equilibrium with a specified, that is, observed field of SST. Hence, any bulk heat fluxes that are computed from ocean model using a reanalysis for boundary conditions will effectively drive the ocean model towards the SST used in that reanalysis. In some sense this is a form of data assimilation, with the model being nudged towards observed SST.

E.6. Needs of managers

Managers have received mandates from the National Environmental Protection Act, the Marine Mammal Protection Act, and the Endangered Species Act. Endangered species include stellar sea lion, sea otters, fur seals, and right and fin whales. An ecosystem approach to management is sought, which is adaptive, regionally directed, and uses ecosystems knowledge. Predictions on scales of 5-10 years are of especial interest. Prime issues include bycatch, indirect effects of fishing, and physical-biological linkages.

Hindcasts of circulation and biology with observed fish stocks can help to establish likely responses of the ecosystem to future change. Important species for the Bering Sea include snow crab, tanner crab, pollock, and salmon.

In general, fisheries managers need new models to generate more helpful indices of fisheries and ecosystem status. Ideally what are sought are models which link physics and climate to recruitment in a realistic fashion, as opposed to simple correlative relationships. Predator/prey overlap and food web structures need to be delineated. Models could be useful in the design of MPAs (e.g. protected reserves).

A useful strategy might be to use a Lower Trophic Level model to feed into higher trophic level models, based on subregions of the Bering Sea (such as the 6 regions now used for the groundfish surveys). Artful aggregation is the key here. The models so developed should be capable of long runs, and accessible as "open source" software for a variety of users. Physical climate scenarios, suitably downscaled to the region, could be used to test the effect of anticipated climate change on the BSAI ecosystems.

E.7. Estimated timetable of new model products and projects

Vertical and Horizontal Resolutions – will indefinitely increase over time

- 1 – 5 km
  - will take 0 – 5 years, region and nesting dependent
  - will take 3 – 5 years for unstructured grids

General Model Improvements

- 2 – 5 years
  - Tidal Mixing Parameterization
  - Hybrid Models for Vertical Coordination
  - 2-way nesting
- 2 – 10 years
  - 2-way Atmosphere/Ocean Coupling

    - Secondary Forcing
- 4 – 5 years
    - Arctic System Reanalysis
        - Historical
        - Improved winds, radiation, and ice
    - PCMDI (Program for Climate Model Diagnosis and Intercomparison) and others – available now for climate projections

<u>Atmospheric Models</u>

- 2 – 5- years
    - Downscaling low/high resolution
- 3 – 5 years
    - Improved radiation
        - Other models needed for Bering Sea Effort

<u>NPZ and Other Upper Trophic Level Models</u>

- 0 – 3 years
    - Adapt existing Bering Sea Models
        - Number of Boxes
        - Add Si, N, Fe, etc
    - Benthic Communities
    - Vertical resolution
        - Physics → Biology
        - Food Web
    - Various Sensitivity Studies
        - Offline
        - 1D, 2D, and reduced 3D
        - Box – single and multi
    - What is the simplest useful NPZ?
    - Upper trophic levels – fish, etc.

        - Include behavior
        - Not necessarily tied to NPZ or physics
        - Spatially explicit box models
        - Spatially explicit stock assessment models

IBMs (Individual Based Models)

- Recruitment studies
- 0 – 5 years
    - genetic algorithms
- 5 – 10 years
    - 2-way coupling
    - Couple IBMs with NPZs as well as ECOSIM

Overall General Issues

- 0 – 3 years
    - Sampling Design
    - Developing Indices
    - Resolution Issues
    - Discussions/Workshops with Management
- 0 – 5 years
    - More biology/physics
    - Model comparisons (both biology and physics)
    - Shared data and models

F. Conclusions

This workshop demonstrated the wide range of modeling approaches currently available, and suggested promising avenues for improvement.

The ideal circulation model would adequately and simultaneously resolve all the relevant scales of motion and phenomena in the BSAI, e.g. flows through the Aleutian Passes, seasonal ice, and tidal mixing on the shelves. None of the present modeling approaches can rapidly and simultaneously capture all of these features for extended time periods on today's computers; fine-scale multi-decadal hindcasts require months of dedicated computer time, even on massively parallel platforms. However, continuing advances in computer technology are expected to expand the limits of feasible simulations, at least doubling the possible spatial resolution for such runs before 2010. Both nested approaches with structured grids, and variable resolution approaches with unstructured grids, appear promising ways forward. Present ice model algorithms appear adequate for the Bering Sea. The accuracy of circulation hindcasts for the BSAI are limited by the paucity of data, especially as regards the passes. Long-term moorings and systematic hydrographic surveys, in conjunction with altimeter data, will help rectify this deficiency; the former are especially valuable on the shelf, given the large spatial correlation scales of that subregion. Effective mathematical approaches are now available in community model codes for assimilation of such data into hindcasts and nowcasts. Computer resources are still a limiting factor in the application of some of these codes. The atmospheric forcing datasets also have outstanding issues (e.g. biased shortwave radiation estimates), which limit the hindcast skill of BSAI simulations, and of ice in particular.

The ideal scientific/management biological model might include multiple species and multiple life stage components, with specific species treated using spatially explicit IBMs, coupled to multi-compartment NPZ and circulation models, all running simultaneously on the same spatial grid and with the same time step. Proper feedback among the different components would be one of the major challenges, especially between IBM and NPZ components. As an intermediate step, more attention could be focused on the coupling of spatially explicit NPZ models with spatially aggregated food web models. For all models, longer time scales are needed than are presently simulated, to aid in ecosystem-based management. Data gaps are even larger for the biology than for the physics of the BSAI, although sustained surveys (e.g. the NMFS groundfish surveys) have yielded much useful data for the quantification of food webs, and both moorings and satellites offer some useful data on phytoplankton.

More collaborative development of both physical and biological models is recommended, as they will require substantial human resources. Indeed, with the advancing spatial and temporal resolution of such models, human time to examine and interpret the output can be just as limiting as computer hardware. One way to ease the development and interpretation of such multi-investigator models is to provide easy access to model output through web-based software.

G. References

Adcroft, A.J., Hill, C.N. and J. Marshall. 1997. Representation of topography by shaved cells in a height coordinate ocean model. *Mon Wea Rev.*, vol 125, 2293-2315

Aydin, K. A., G. A. McFarlane, J. R. King, B. A. Megrey, and K. W. Myers. 2005. Linking oceanic food webs to coastalproduction and growth rates of Pacific salmon (Oncorhynchus spp.), using models on three scales. *Deep-Sea Research II*, 52: 757–780.

Bleck, R., 2002: An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates. *Ocean Modelling*, 4, 55-88.

Bleck, R., and D. B. Boudra, 1981: Initial testing of a numerical ocean circulation model using a hybrid (quasi-isopycnic) vertical coordinate. *J. Phys. Oceanogr*., 11, 755-770.

Blumberg, A. F. and G. L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model, In *Three-Dimensional Coastal Ocean Models*, N. S. Heaps (Ed.), 1-16, American Geophysical Union, Washington, DC.

Budgell, W. P. 2005. Numerical simulation of ice-ocean variability in the Barents Sea region: Towards dynamical downscaling. *Ocean Dyn.* **55**: 370-387.

Chassignet, E., L. Smith, G. Halliwell, and R. Bleck, 2003. North Atlantic simulations with the HYbrid Coordinate Ocean Model (HYCOM): Impact of the vertical coordinate choice, reference pressure, and thermobaricity. *J. Phys. Oceanogr*. 33, 2504-2526.

Curchitser, E. N., D. B. Haidvogel, A. J. Hermann, E. L. Dobbins, T. M. Powell, and A. Kaplan. 2005. Multi-scale modeling of the North Pacific Ocean I: Assessment and analysis of simulated basin-scale variability (1996-2003). *J. Geophys. Res.,* 110: C11021.

Haidvogel, D. B., H. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, and A.Shchepetkin, 2000. Model evaluation experiments in the North Atlantic Basin: Simulations in non-linear terrain-following coordinates. *Dyn Atmospheres and Oceans* 32, 239--281.

Haidvogel, D. B., J. L. Wilkin, and R. Young. 1991. A semi-spectral primitive equation ocean circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. *J. Comput. Phys.* 94: 151-185.

Haidvogel, D. B., E. N. Curchitser, M. Iskandarani, R. Hughes, and M. Taylor, 1997. Global modeling of the ocean and atmosphere using the spectral element method. *Ocean-Atmosphere*, 35 (1): 505-531

Hermann, A. J., P. J. Stabeno. D. B. Haidvogel and D. L. Musgrave. 2002b. A regional tidal/subtidal circulation model of the southeastern Bering Sea: Development, sensitivity analyses and hindcasting. *Deep-Sea Res. II (Topical Studies in Oceanography)* 49: 5495-5967.

Hibler, III, W. D. 1979. A Dynamic Thermodynamic Sea Ice Model. *J. Phys. Oceanogr.* **9**: 815-845.

Hunt, G. L., P. J. Stabeno., G. Walters, E. Sinclair, R. D. Brodeur, J. M. Napp, and N. A. Bond. 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. *Deep-Sea Res. II* 49: 5821-5853.

Ladd, C., and N.A. Bond, 2002: Evaluation of the NCEP-NCAR Reanalysis in the northeast Pacific and the Bering Sea. *J. Geophys. Res*.,107(C10), 3158, 10.1029/2001JC001157.

Large, W.G., J.C. McWilliams, and S.C. Doney, 1994. Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Rev. Geophys. Space Phys.* 32: 363–403.

Moore, A. M., H. G. Arango, E. DiLorenzo, B. D. Cornuelle, A. J. Miller, and D. J. Neilsen. 2004a. A comprehensive ocean prediction and analysis system based on the tangent linear and adjoint of a regional ocean model, *Ocean Modeling,* 7: 227-258.

Mantua, N., S. Hare, Y. Zhang, J. Wallace, and R. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.*, 78, 1069-1079

Mellor, G. and T. Yamada, 1982. Development of a Turbulence Closure Model for Geophysical Fluid Problems, *Rev. Geophy. Space Phys*. 20 (4): 851.

Pacanowski, R. C., and S. M. Griffies, 1998: MOM 3.0 Manual, NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, USA 08542.

Price, J. F., R. A. Weller, and R. Pinkel, 1986. Diurnal cycling: Observations and models of theupper ocean response to diurnal heating, cooling, and wind mixing. *J. Geophys. Res.* 91:8411-8427.

Schumacher, J.D., and P.J. Stabeno. 1998. The continental shelf of the Bering Sea. In: A.R. Robinson and K.H. Brink (eds.), *The Sea: The global coastal ocean regional studies and synthesis*, Vol. XI. John Wiley and Sons, New York, pp. 869–909.

Shchepetkin, A. F., and J. C. McWilliams. 2004. The Regional Ocean Modeling System:

A split-explicit, free-surface, topography-following coordinate ocean model, *Ocean Modeling*, 4: 347-404.

Springer, A.M., C. P. McRoy, and M. V. Flint. 1996. The Bering Sea Greenbelt: shelf-edge processes and ecosystem production. *Fisheries Oceanography*, 5: 205–223.

Stabeno, P.J., J.D. Schumacher, and K. Ohtani, 1999. The physical oceanography of the Bering Sea. In *Dynamics of the Bering Sea: A Summary of Physical, Chemical, and Biological Characteristics, and a Synopsis of Research on the Bering Sea*, T.R. Loughlin and K. Ohtani (eds.), University of Alaska Sea Grant, AK-SG-99-03, North Pacific Marine Science Organization (PICES), 1–28.

Stabeno, P.J., D.K. Kachel, N.B. Kachel, and M.A. Sullivan, 2005. Observations from moorings in the Aleutian passes: Temperature, salinity, and transport. *Fish. Oceanogr.* Supplemental Issue on the Aleutian Islands Ecosystem [In press].

Stabeno, P.J., N.A. Bond, and S.A. Salo (2006): On the recent warming of the southeastern Bering Sea Shelf. *Prog. Oceanogr.* [accepted].

Thompson, D.W.J., and J.M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, 25, 1297-1300.

Baptista, A. M., Y. L. Zhang, A. Chawla, M. Zulauf, C. Seaton, E. P. Myers, III, J. Kindle, M. Wilkin, M. Burla, and P. J. Turner. 2005. "A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: II. Application to the Columbia River," *Continental Shelf Research*, vol. 25, pp. 935-972.

Zhang, Y. L., A. M. Baptista, and E. P. Myers. 2004. "A cross-scale model for 3D baroclinic circulation in estuary-plume-shelf systems: I. Formulation and skill assessment," *Continental Shelf Research*, vol. 24, pp. 2187-2214.

Chen, C. H. Liu, R. C. Beardsley, 2002. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. *Journal of Atmospheric and Oceanic Technology*,20, 159-186.

Vance, T.C., J.D. Schumacher, P.J. Stabeno, C.T. Baier, T. Wyllie-Echeverria, C.T. Tynan, R.D. Brodeur, J.M. Napp, K.O. Coyle, M.B. Decker, G.L. Hunt, Jr., D. Stockwell, T.E. Whitledge, M. Jump, and S. Zeeman (1998): Aquamarine waters recorded for first time in eastern Bering Sea. *Eos Trans. Am. Geophys. Union, 79*(10), 121, 126.

H.1. Agenda of the Workshop

Agenda for the Workshop to Evaluate Ocean Circulation Models for the Bering Sea and Aleutian Island Regions

Thursday and Friday, February 3-4, 2005

Pacific Marine Environmental Laboratory (PMEL), Seattle, Washington

Thursday, February 3

8:00 Coffee, Welcome, Business. Dave Musgrave (University of Alaska Fairbanks)
8:15 Purpose. Al Hermann (Pacific Marine Environmental Laboratory, Joint Institute for the Study of Atmospheres and Oceans)
8:30 Observations of relevant physical oceanographic features and processes in the BSAI region. Phyllis Stabeno AND/OR Carol Ladd (Pacific Marine Environmental Laboratory)
8:55 Forcing mechanisms in the BSAI region. Jim Overland AND/OR Nick Bond (Pacific Marine Environmental Laboratory)
9:20 Ocean model types: Z-coordinate, terrain-following and layered models. Dale Haidvogel (Rutgers)
9:55 Break for 25 min
10:20 Unstructured grids for ocean models. Antonio Baptista (Oregon Graduate Institute)
10:45 Data assimilation methods for ocean circulation models. Art Miller (Scripps Institution of Oceanography)
11:10 Ice models. Greg Flato (Canadian Centre for Climate Modelling and Analysis)
11:35 Management needs within the BSAI region. Pat Livingston (National Marine Fisheries Center)

12:00 Lunch

1:00 Ecosystem models and individual based models within ocean circulation models. Sarah Hinckley (National Marine Fisheries Center)
1:25 Extant ocean circulation models of the Bering Sea and Aleutian Island Region. Al Hermann, Wieslaw Maslowski (Naval Postgraduate School), Jia Wang (University of Alaska Fairbanks)
1:25 Instructions for working groups. Dave Musgrave
2:15 Working groups on needs assessment. (Break when needed.)

A. Fisheries and Ecosystem. Leader: Clarence Pautzke (North Pacific Research Board)
B. Climate Change. Leader: Mark Johnson (University of Alaska Fairbanks)
C. Ocean Observing Systems. Leader: Bern Megrey (Alaska Ocean Observing System)

4:30 Reports from Working Groups

Friday, February 4

8:30 Instructions to Working Groups. Dave Musgrave

8:45 – 11:30 Working groups on matching needs to models. (Break when needed.)

A. Fisheries and Ecosystem. Leader: Pat Livingston
B. Climate Change. Leader: Wieslaw Maslowski
C. Ocean Observing Systems. Leader: Yi Chao (Jet Propulsion Lab)

10:15 Working group reports

11:30 Working group reports

12:00 Lunch

1:00 Working groups on observational needs and data assimilation techniques

A. Leader: Susan Allen (University of British Columbia)
B. Leader: Xavier Capet (University of California Los Angeles)
C. Leader: Phyllis Stabeno

2:30 Working group reports

3:00 Working groups on pathways for using models to develop products for resource managers (synthesis of prior working groups).

A. Leader: Yi Chao
B. Leader: Dale Haidvogel

4:00 Working group reports

5:00 Adjourn.

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H.3. Extended Abstracts

Forcing Mechanisms in the BSAI Region

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This presentation had three elements: a review of new perspectives on the North Pacific ocean-atmosphere climate system, a brief summary on the recent state of the Bering Sea, and a discussion of issues related to forcing numerical ocean models with currently available reanalysis products for the atmosphere.

There is increasing appreciation that the Pacific Decadal Oscillation or PDO (Mantua et al. 1997) does not fully describe important aspects of the North Pacific atmosphere-ocean climate system. The shift in the PDO in 1976-77 did represent the most systematic transition in the North Pacific climate and marine ecosystem of the last half century. But for the period from the early 1990s to 2002, the second mode (based on EOF analysis) has dominated North Pacific variability. Notably, the state of this mode from 1998 through 2002 supported atmospheric forcing of an anomalously strong sub-arctic gyre in the North Pacific. At present, the state of the wintertime North Pacific is characterized by weak and inconsistent signals in both of its two leading modes. Moreover, clear indications of the current trajectory of the North Pacific climate system is lacking. Greater attention is starting to be paid to the North Pacific climate system during the warm season. The PDO does have a substantial expression at this time of year, but the second mode of variability is much different than that during the cold season. It consists of a pattern with the amplitude of SST anomalies increasing poleward; its existence appears to reflect a warming trend over the last 4 decades for the region stretching from the Aleutians to the northern Gulf of Alaska. The linkages between the summertime state of the North Pacific atmosphere-ocean and the marine ecosystem are only beginning to be explored.

The Bering Sea has undergone a remarkable warming. While the incidence of relatively cold winters has been decreasing in frequency, as apparent in time series of seasonal ice cover, secular warming is especially apparent in summer. For example, each of the summers of 2002 through 2004 featured vertically integrated heat contents greater than any previously recorded.
Part of this recent warmth can be attributed to the recent overall sense of the Arctic Oscillation or AO (Thompson and Wallace 1998). Unlike the Eurasian sector of the Arctic, the Bering Sea and Alaska tend to be cooler than normal when the AO is in a positive state. This effect is due to the AO□s influence on sea level pressure in the vicinity of the Aleutian low, and ultimately, the favoring of cyclones with warm, maritime origins versus anticyclones of cold, arctic or continental origins. The AO has tended to be in a neutral to negative state since about 1996, thereby promoting warm winters, reduced sea ice, earlier onsets of spring, and finally, warmer ocean temperatures in summer. The role of ocean dynamics in the trends seen in the Bering Sea has not yet

been determined.

The atmospheric structure in the BSAI region over the last 5-6 decades can be described using reanalysis products from centers such as NCEP, but there are issues regarding these reanalysis products in the forcing of ocean numerical models. One of these issues relates to how air-sea interactions constrain surface thermodynamic fields in reanalyses. The near surface atmosphere in these products are generally in near equilibrium with a specified, that is, observed field of SST. The fluxes that are computed from ocean model using a reanalysis for boundary conditions will effectively drive the ocean model towards the SST used in the reanalysis in the first place. Perhaps an even more vexing issue relates to systematic errors in an important component of the net heat fluxes at the air-sea interface. Specifically at least for the NCEP Reanalysis, there is considerable evidence (Ladd and Bond 2002) for underestimation of low cloud coverage and hence overestimation of insolation during the warm season. This error is partly offset by a concomitant error of the opposite sense in the downward longwave radiative flux. The problem is more pronounced during high pressure, fair-weather conditions. Users of the NCEP Reanalysis (it is unknown whether the ERA-40 product from ECMWF includes a similar bias) may have to apply ad-hoc corrections to avoid unrealistic heating by as much as 30 W/m2 in the BSAI region.

Ladd, C., and N.A. Bond, 2002: Evaluation of the NCEP-NCAR Reanalysis in the northeast Pacific and the Bering Sea. J. Geophys. Res.,107(C10), 3158, 10.1029/2001JC001157.

Mantua, N., S. Hare, Y. Zhang, J. Wallace, and R. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc., 78, 1069-1079.

Thompson, D.W.J., and J.M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett., 25, 1297-1300.

Numerical Ocean Circulation Models: Past, Present and Future

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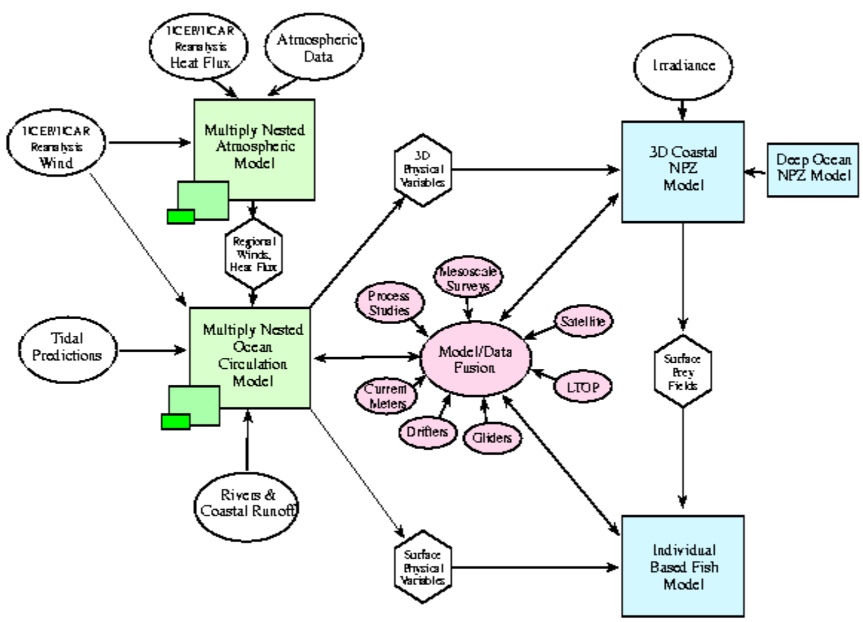
Ocean circulation models have recently achieved an impressive level of sophistication. Important new capabilities include: generalized vertical coordinate systems allowing more effective transition across the deep/coastal ocean boundary; well developed sub-models for the evolution of coupled biological and geochemical tracers; robust procedures for one-way nesting of models with differing spatial windows and resolution; efficient algorithms for multi-variate data assimilation; and pre-operational prediction systems for global, regional and local areas. Over the next five years, further progress is anticipated, including the refinement of operational forecast and analysis systems for the North Atlantic and other regions, the emergence of powerful alternatives for multi-scale ocean modeling including adaptive unstructured grid techniques, and the availability of new approaches for interdisciplinary modeling and data assimilation.

We review these emerging capabilities. Using the U.S. GLOBEC program as an example, we discuss the development and status of end-to-end multi-scale modeling systems for coupled ecosystem studies. Examples, drawn from an ongoing suite of nested modeling projects in the Western North Atlantic, are described.



NPZ and Individual-based Models (IBMs) in the Bering Sea/Aleutian Islands

S. Hinckley

The first consideration when assessing what biological models are needed for the Bering Sea-Aleutian Islands (BSAI) region, is what are the questions being asked? Unlike physical models, where the underlying equations of motion are fairly well known and understood, there is no such comparable set of biological equations. There is no single all-encompassing biological model, nor can there be, due to the complexity of the ecosystems and biological components and mechanism underlying them. Biological model choice is heavily dependent on the specific question being asked.

Regional NPZ Models

There are few groups doing 3D NPZ models in the BSAI region. Hinckley, Hermann et al. have an 11-compartment 3D NPZ model that has been developed for the GOA under the GLOBEC NEP program and implemented in the physical ROMS model. When run on the 10 km NEP grid (see Hermann, this report), this model has also been implemented for the Bering Sea. Presently this model consists of 11 compartments. Iron was included to allow the simultaneous modelling of both HNLC (iron-limited) ecosystems such as the deeper oceanic areas, as well as the coastal ocean. Some changes to model compartments would be needed to adapt this NPZ model to the Bering Sea ecosystem. These might include parameterization of the euphausiid compartment for *Thysanoessa*, spp. instead of *Euphausia pacifica*, the addition of *Calanus marshallae,* and the inclusion of low-temperature Q10s and other rates affected by the lower temperatures of the region.

Hinckley, Hermann et al. have also developed a 3D NPZ model specifically designed to provide a spatially and temporally dynamic prey field for young walleye pollock modelled with an IBM (see below). This NPZ model was designed for the Shelikof Strait and western GOA region. It includes compartments for nitrogen, phytoplankton, *Neocalanus*, spp. (as the biomass dominant grazer) and 13 stages of *Pseudocalanus*, spp. which provide the food source for young pollock larvae. This model could also be reparameterized for the Bering Sea, and run within the ROMs model, however, there are no present plans to do so.

J. Wang and C. Diehl of the Arctic group at UAF have a 3D NPZ model for the Bering Sea. The NEMURO model, a 1D (water column) ecosystem model developed under the auspices of the PICES Model Task Team, has been implemented in the Bering Sea (Megrey, this report) and other regions. Merico et al. (2004) have a two-layer water column model of phytoplankton succession for the Bering Sea. There are also some global climate/ocean models that include NPZ models, but these are highly biologically aggregated, basin scale models which use large grid resolutions, and are not very detailed in regions such as the BSAI.

If one were to construct an NPZ model for the BSAI region in order, for example, to look at production changes in response to climate change, what would this model need to be able to do? There are many features of the BSAI and its ecosystems that such a model would need to be able to replicate, for example, ice-edge and normal spring blooms, the frontal structures and differences in communities by domain (e.g. the benthic ecosystem of the inner-middle shelf and the pelagic ecosystem of the outer shelf, slope and basin), and the Green Belt. One might want to include coccolithophores, or important prey for fish, seabirds or marine mammals, if the purpose of the model was to couple with an IBM. Diapause of large oceanic copepods, and the transport of these and other ecosystem components on and off the shelf may also be important to the questions being asked.

What compartments might this NPZ model need? The following are probably the most important, but the degree of aggregation, again, depends on the questions being asked. Compartments for the benthos, detritus, small and large phytoplankton, small and large microzooplankton, and large oceanic copepods would be of use, and perhaps *Calanus marshallae*, *Acartia*, and/or *Pseudocalanus*, spp., and one or more euphausiids. One might want to include jellyfish, as they are a ubiquitous part of the Bering Sea ecosystem in summer. A compartment for iron may be necessary, if HNLC conditions are present in the deeper waters. It may be necessary to model silicate as well.

Individual-based Models

IBMs are constructed for many different purposes. When coupled with 3D ocean models, they are uniquely suited for the examination of problems related to transport of planktonic organisms, which may be tracked in a Lagrangian manner in coupled IBM/hydrodynamic models; and for the examination of mechanisms and processes affecting individuals which might be lost in an aggregated population or Eulerian model. It is possible to include complex behaviors and interactions between individuals where these are known and thought to be important. IBMs require large amounts of data however, on processes, rates and behaviors and their physical driving functions. For many species, this information is not available. Although float tracking without biology in 3D physical models can yield important information, IBMs also usually have bioenergetics and behavioral mechanisms included that are specific to the species under investigation. Most commonly, at least in marine systems, IBMs have been constructed to study plankton transport, bioenergetics and behavior, fish recruitment, egg, larval and juvenile transport and bioenergetics and behavior, and adult fish migration and bioenergetics. The last can be very difficult, as parameterizations of movement, migration and schooling behavior may be needed and information on these is often sparse.

Hinckley, Hermann, et al. have built IBMs of walleye pollock early life stages (from the spawning of eggs, through larval and 0-age juveniles in the fall) for both the western GOA and the Bering Sea. The GOA pollock IBM has been coupled with the SPEM hydrodynamic model and the NPZ model described above, and used to study recruitment variability in this stock. A study is presently underway with this model to develop a pre-recruit index from the model that may be useful to management. The Bering Sea pollock IBM was developed under the auspices of the SEBSCC program, however the physical model available at the time was constructed for other purposes, and did not have the correct domain to utilize with the pollock IBM for the study of recruitment in this region.

Interest has been expressed in developing IBMs for crab, winter spawning flatfish and euphausiids in the BSAI, however this will be dependent of data availability and funding.

Naval Postgraduate School Pan-Arctic Modeling Effort: Model Description

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The Naval Postgraduate School coupled ice-ocean model domain has been chosen to allow focused studies of the circulation and exchanges between the sub-arctic and arctic basins and to include all seasonally sea ice covered seas of the Northern Hemisphere. It extends from about 30°N in the North Pacific, including the Sea of Japan, Sea of Okhotsk, and Gulf of Alaska, through the Bering Sea, Arctic Ocean, Canadian Archipelago, Nordic and Barents seas into the North Atlantic to about 45°N. The numerical grid is configured at 1/12° (or ~9 km) and 45 levels using rotated spherical coordinates. Given the entire model domain, the horizontal resolution is considered eddy permitting as features down to ~40 km (four grid points) can be resolved. This might be sufficient horizontal resolution to resolve larger mesoscale eddies in the North Pacific, Bering Sea, and North Atlantic but not the smaller mesoscale eddies more characteristic of the Arctic Ocean. In the vertical direction, the model uses fixed layers with thickness ranging from 5 meters at the surface to 300 meters at depth. There are eleven layers in the first 100 meters and nineteen layers in the upper 500 meters. At depths below 1000 m, twenty-two layers with thickness of 200-300 meters are defined. The maximum model depth is set to 6250 meters for numerical efficiency, which affects the deepest parts of the Aleutian Trench but does not change the overall circulation in the region.

One of the important features of model setup is an artificial channel opened across Canada from the Atlantic to the Pacific Ocean. It allows a return flow needed to balance the net northward transport through Bering Strait (Maslowski *et al.*, 2004). The predicted mean net volume transport through Bering Strait for 1979-2001 is between 0.65 and 0.80 Sv (Clement *et al*., 2004), which compares well with the mean northward transport of 0.83 Sv estimated from limited direct current measurements in the early 1990s (Roach *et al*., 1995). We argue that the net northward transport from the North Pacific, through the Bering Sea into the Arctic Ocean has important consequences not only on the local currents at the strait and downstream environment but also upstream, on the removal of fresh water from and on the circulation and upper ocean mass structure in the Bering Sea and in the Alaskan Gyre.

The ice-ocean model consists of a regional adaptation of the global Parallel Ocean Program (POP) model, including a free surface method (Dukowicz and Smith, 1994; Maslowski *et al*., 2004), coupled to a sea ice model with viscous-plastic ice rheology (Zhang *et al.*, 1999; Maslowski and Lipscomb, 2003). The combination of high resolution with the free surface approach allows use of unsmoothed and realistic bathymetry, including islands, shelves, and steep depth gradients associated with many continental slopes. The model lateral boundaries, including those for river runoff, are closed, allowing no mass or momentum transfer across them.

The five-meter thin ocean surface level is restored on a monthly timescale to monthly PHC temperature and salinity climatology, as a correction term to the explicitly calculated fluxes between the ocean and overlying atmosphere or sea ice. A ten-day restoring to annual PHC temperature and salinity climatology is applied along the lateral boundaries to minimize their local effects on the circulation and water mass properties. At river mouths (Yukon, Mackenzie, Ob, Yenisey, Lena, Katanga, Dvina, Pechora, Kolyma and Indigirka) daily-averaged annual cycles of salinity and temperature are prescribed as a function of each river's volume transport. Additional details about the model, boundary conditions, and atmospheric forcing are discussed by Maslowski *et al.* (2004) and Maslowski and Lipscomb (2003).

The ocean model was initialized with climatological, 3-dimensional temperature and salinity fields (PHC, Steele *et al.*, 2000) and integrated for 48 years in a spinup mode first using climatological atmospheric forcing derived from 1979-1993 ECMWF reanalysis (for 27 years) and then repeated 1979-1981 daily averaged fields (for 21 years). This spinup approach is especially important to establishing realistic ocean circulation representative of the time period at the beginning of the final integration with daily-averaged interannual forcing, which starts in 1979 and continues through 2003. These results are available for focused regional analyses and for forcing of ecosystem models (e.g. NPZ or IBM models).

In studies focused on the Aleutian Island Passes and the Bering Sea, which include coastal currents, small eddies, and local topography-driven flows, even higher resolution is needed. However, such local process studies require understanding of large-scale circulation and its variability to provide adequate boundary conditions. Therefore, a large domain or some type of nesting is often needed. Another issue has to do with tides, which contribute to the dynamics in the Aleutian Island passes at 1-10 day time scales and which are not included in this model version. Investigations of the influence of tides as well as coastal and topography controlled currents and small eddies on the marine ecosystem of the Aleutian Islands and Bering Sea are planned with subsequent model versions incorporating tides and configured at even higher resolution.

References:

Clement, J.L., Maslowski, W., Cooper, L.W., Grebmeier, J.M., Walczowski, W. (2005) Ocean circulation and exchanges through the northern Bering Sea – 1979-2001 model results. Deep-Sea Res., submitted.

Maslowski, W., Marble, D., Walczowski, W., Schauer, U., Clement, J. L., Semtner, A. J. (2004) On climatological mass, heat and salt transports through the Barents Sea and Fram Strait from a pan-Arctic coupled ice-ocean model simulation. *J. Geophys. Res.* **109**, C03032, doi:10.1029/2001JC001039..

Maslowski, W., and Lipscomb, W.H. (2003) High-resolution simulations of Arctic sea ice during 1979-1993. *Polar Res.* **22:** 67-74.

Roach, A.T., Aagaard, K., Pease, C.H., Salo, S.A., Weingartner, T., Pavlov, V., and Kulakov, M. (1995) Direct measurements of transport and water properties through Bering Strait. *J. Geophys. Res.* **100:** 18443-18458.

Steele, M., R. Morley, W. Ermold, 2000. PHC: A global ocean hydrography with a high quality Arctic Ocean. Journal of Climate, 14(9), 2079-2087.

Zhang, Y., Maslowski, W., and Semtner, A.J. (1999) Impact of mesoscale ocean currents on sea ice in high-resolution Arctic ice and ocean simulations. *J. Geophys. Res.* **104 (C8):** 18409-18429.