Biophysical modeling of Pacific High-Latitude Ecosystems and its application to marine resource management

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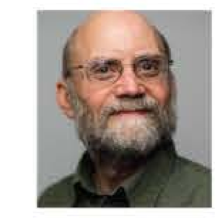
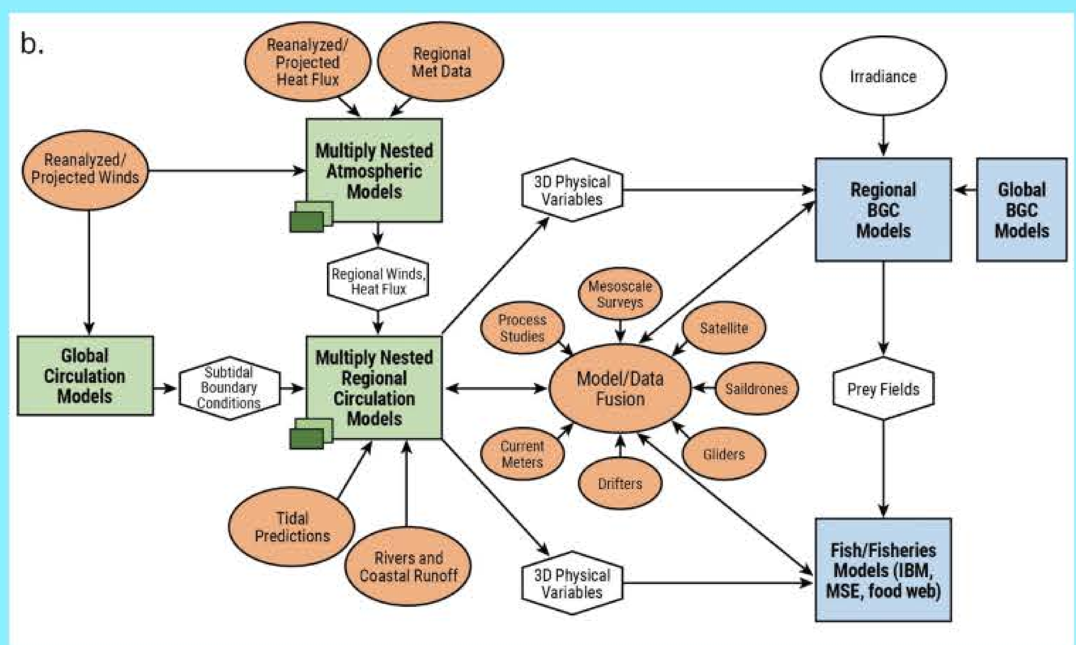
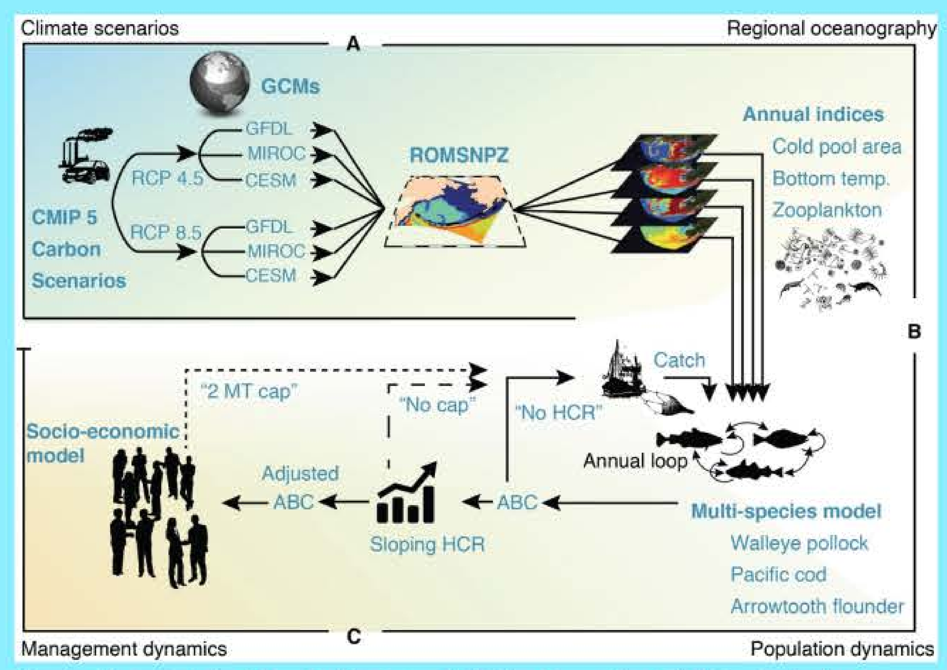


Societal needs for regional downscaling

Global earth system models assimilate data to replicate past conditions, and are used to project future conditions. To examine the life histories of managed marine species, we require *downscaling* of these global products to regional scales. We achieve this through regional dynamical models based on known physical/chemical equations (including carbonate) and hypothesized biological dynamics.



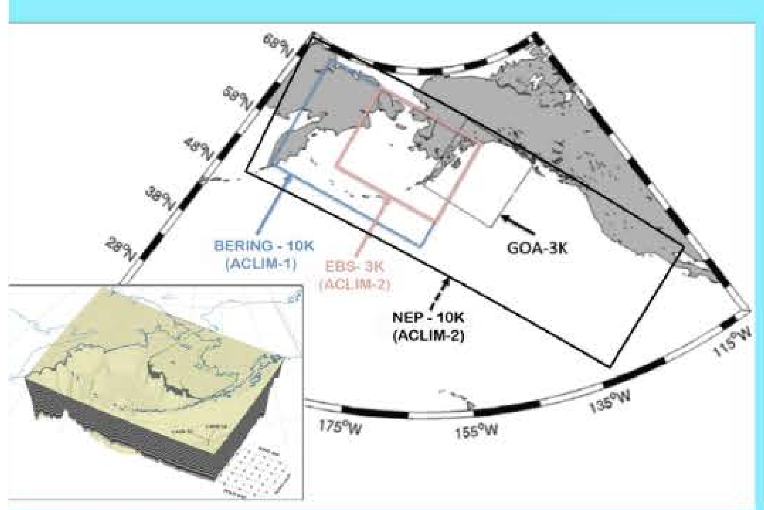
Flowchart of hydrodynamic model forcing, nesting, comparisons with data, and linkage with biological models. Modified from unpublished GLOBEC flowchart by E. L. Dobbins, University of Alaska Fairbanks



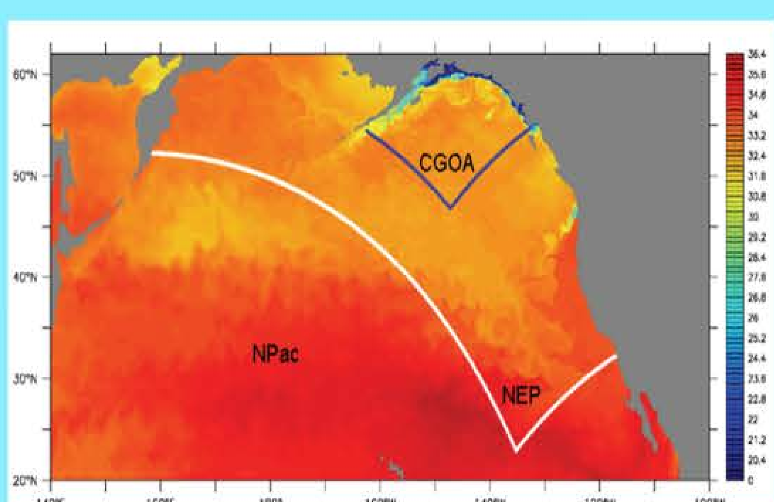
Flowchart illustrating Regional Ocean Modeling System (ROMS)-based downscaling of global climate projections to regional scale in the Bering Sea for use in Management Strategy Evaluation. From ACLIM program, Holsman et al. (2020)

Model nesting

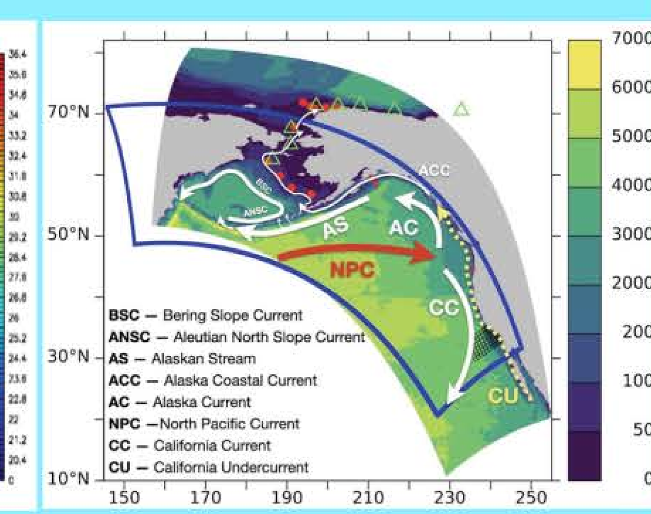
Spatial nesting of regional models provides an affordable way to replicate fine-scale dynamics, guided by larger-scale conditions. For example, we have used simulations of the North Pacific (NPac, from Cuchitser et al. 2005) at 40 km resolution as boundary conditions on a Northeast Pacific model (NEP) at 10 km resolution, which in turn serve and boundary conditions for a Gulf of Alaska model (GOA) at 3 km resolution. Under CEFI, using MOM6, a new regional grid (MOM6-NEP) spans from California to the Chukchi Sea.



Map of regional domains used in our ROMS-based modeling studies



Sea surface salinity from a triply-nested set of ROMS-based regional simulations

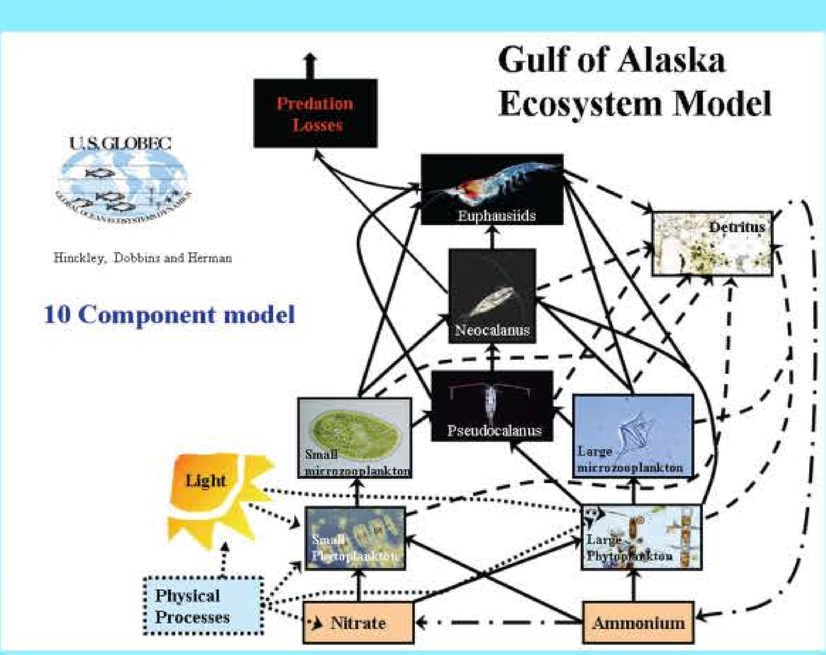


Domain covered by MOM6-NEP model for CEFI program
Color shade: MOM6-NEP model domain and bathymetry
Blue box: ROMS NEP domain
Red dots = EcoFOCI moorings used for calibration/validation

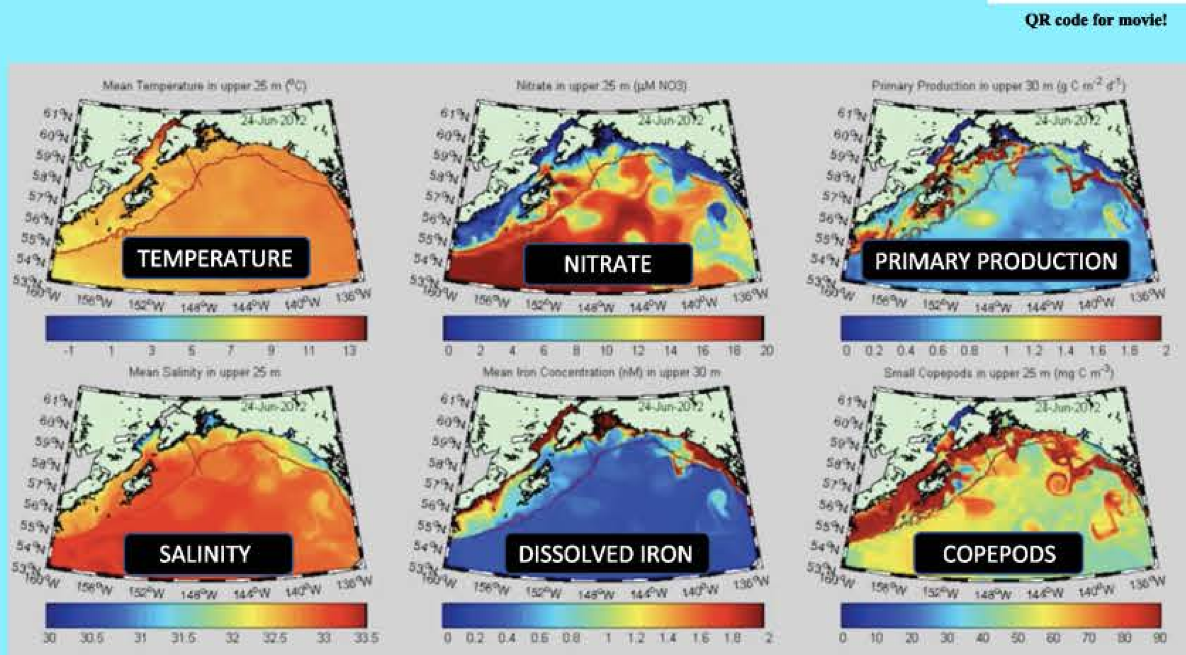
Biogeochemical modeling

We have incorporated biogeochemical models of increasing complexity (including carbonate dynamics) into our regional simulations, to explore past, present, seasonal predicted and future projected conditions relevant to fisheries and their management. One example is our ROMS-based simulations of the Gulf of Alaska. Shown here are the structure of the lower trophic level model, and daily averaged results from mid-June 2012. The QR code at right leads to an animation of multiyear change spanning 1996-2020.

QR code for movie!



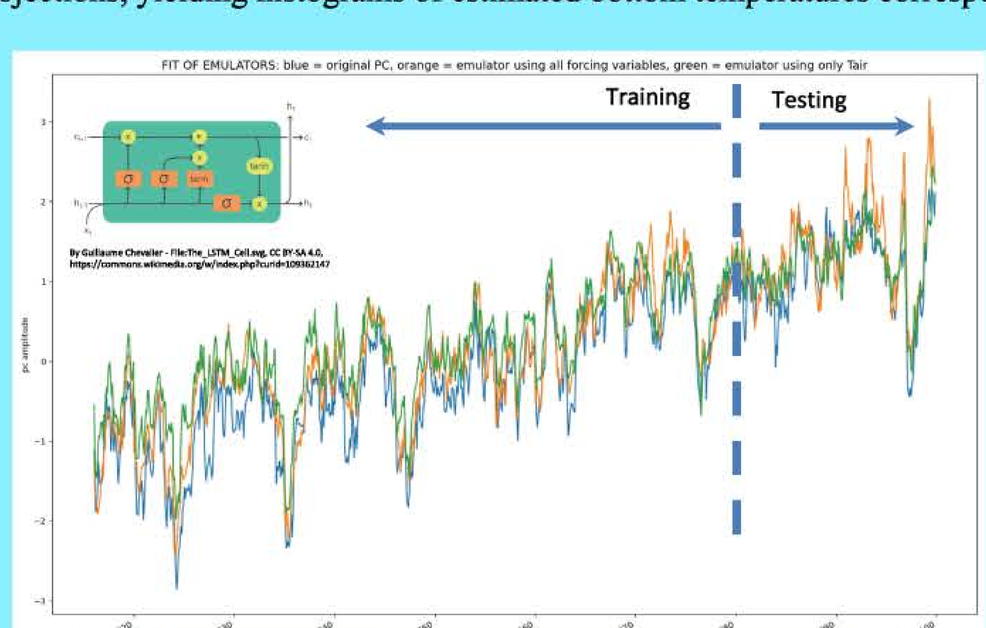
Gulf of Alaska biogeophysical model structure



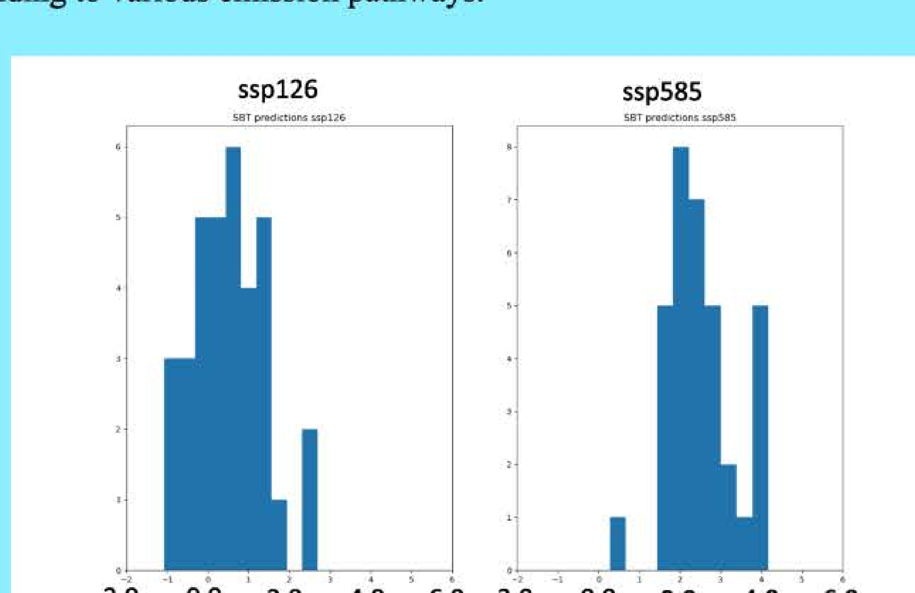
Gulf of Alaska biogeophysical model output (mid-June 2012)

Machine Learning

New approaches based on machine learning offer possibilities to compactly and quickly emulate the dynamics of complex biogeochemical models. We have begun exploring these methods as a way to expand our ensembles of projections, thereby providing better estimates of uncertainty for use by fisheries managers. In the example shown here, we combine traditional dimensional reduction (EOFs) with a Long Short-Term Memory Neural Network (LSTM) to emulate ROMS-based dynamical downscaling. The emulator is trained with ROMS forcing and results from 2015-2080, and tested on results from 2081-2100. The trained model is then driven with a large ensemble of atmospheric forcings from 30 different global model projections, yielding histograms of estimated bottom temperatures corresponding to various emission pathways.



Projected 3D mode of ocean temperature in the Gulf of Alaska:
blue = results from ROMS
orange = results from ML-based emulator
green = results from ML-based emulator based on air temperature



Histograms of projected change in July bottom temperature (2015 to 2100, deg C) near Shelikof Strait under two different socioeconomic pathways (ssp126 = low emission future, ssp585 = high emission future)

A progression of models

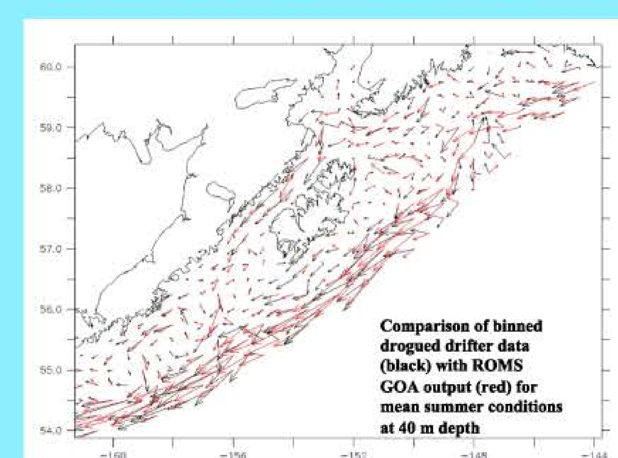
Over the years at PMEL we have utilized increasingly sophisticated ocean models to achieve our goals. These include:
Semispectral Primitive Equation Model (SPEM) - curvilinear and terrain-following, no free surface
S-coordinate Rutgers University Model (SCRUM) - curvilinear and terrain-following with free surface
Regional Ocean Modeling System (ROMS) - improved physics, includes biogeochemical options
Modular Ocean Model, version 6 (MOM6) - fast performance and global biogeochemistry

MOM6 is a central element of NOAAs new *Climate and Ecosystems Fisheries Initiative* (CEFI)

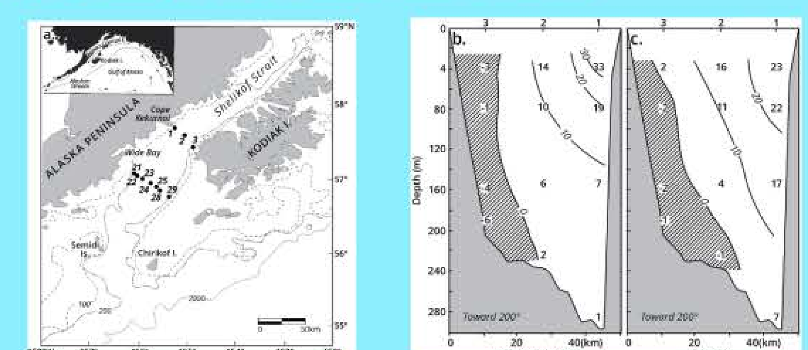
SPEM 1990's → SCRUM 1990-2000's → ROMS 2000's to now → MOM6 Ongoing CEFI

Model-data comparisons

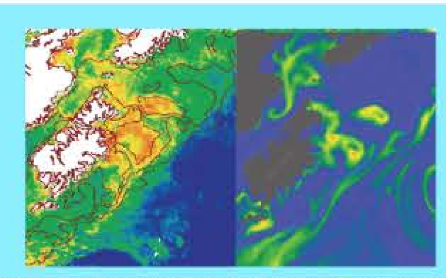
Model tuning and validation has been guided by EcoFOCI data from fixed moorings, shipboard surveys, drifters, and autonomous vehicles, as well as satellite data. Long time series from the fixed biophysical moorings have been invaluable in establishing our models' ability to faithfully capture daily through interannual variability.



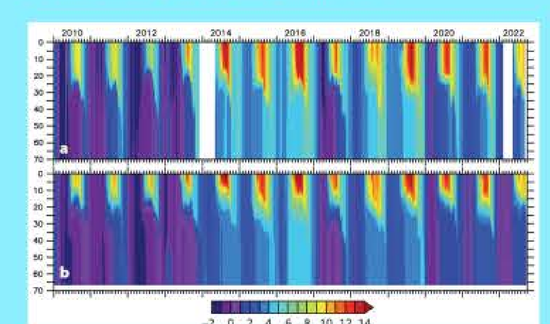
Comparison of binned drogued drifter data (black) with ROMS GOA output (red) for mean summer conditions at 40 m depth



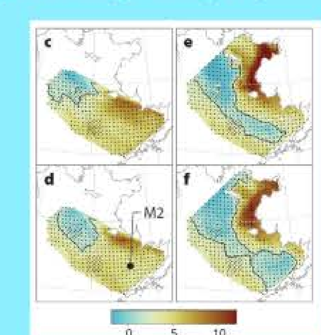
Comparison of moored current meter data and the Semi-spectral Primitive Equation Model (SPEM) for the northern Gulf of Alaska (a, with moorings numbered), illustrating observed (b) and modeled (c) velocities (cm s–1) off Cape Kekurnoi using data from moorings 1–3.



Satellite-derived average July surface chlorophyll concentration (left) compared with daily average (July 21, 2001) from a biogeochemical model of the Gulf of Alaska (right; red/blue = high/low chl concentration)



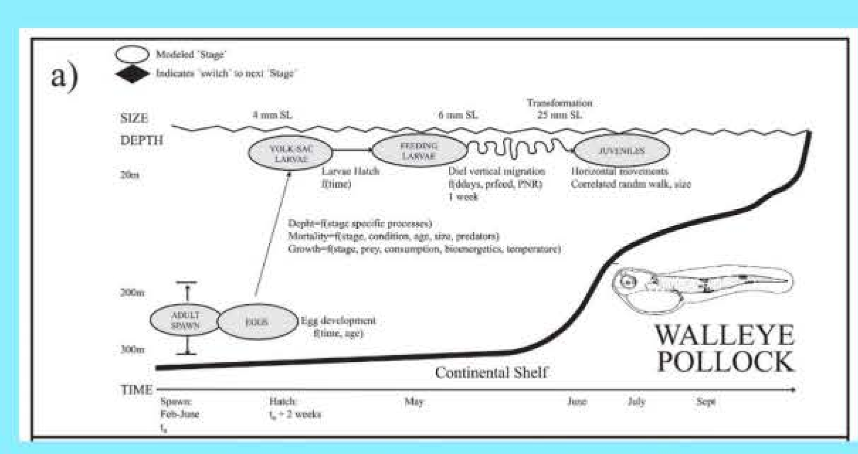
Comparison of (a) biophysical mooring temperature data (°C) with (b) ROMS Bering-10K model output at station M2, a long-term biophysical mooring maintained by EcoFOCI in the southeastern Bering Sea.



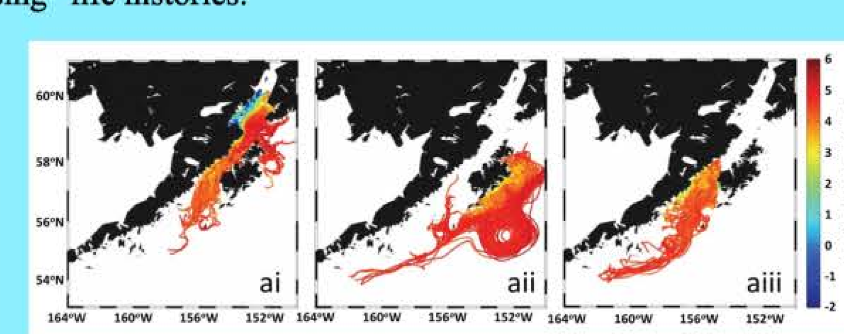
Comparison of measured July bottom temperatures from field surveys (c,e) with ROMS Bering-10K modeled bottom temperatures (d,f), illustrating warm (2016; c,d) and cold (2017; e,f) years. Small black dots indicate sampling locations. Location of station M2 is noted.

Individual-Based Modeling

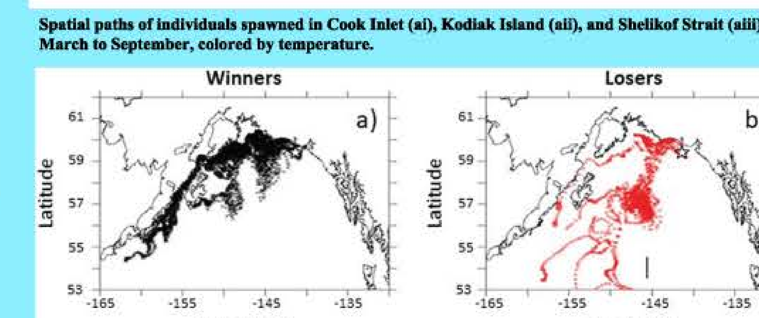
This modeling technique treats fish and mammals as individuals subject to both advection and self-directed motions. One great motivator for this individual-based approach is the classic dictum (historically attributed to Dr. Gary Sharp) that "the average fish is dead"—that is, only a fortunate few survive to adulthood, and we should focus on what makes them successful, rather than on the average (hence unsuccessful) individual. NOAA and university colleagues have utilized our regional model output to drive a variety of individual-based models (IBMs) for walleye pollock, rockfish, sablefish, snow crabs, and many other species to explore "winning" and "losing" life histories.



Schematic of Individual-based model of walleye pollock (from Gibson et al. 2022)



Spatial paths of individuals spawned in Cook Inlet (ai), Kodiak Island (aii), and Shelikof Strait (aiii) between March to September, colored by temperature.

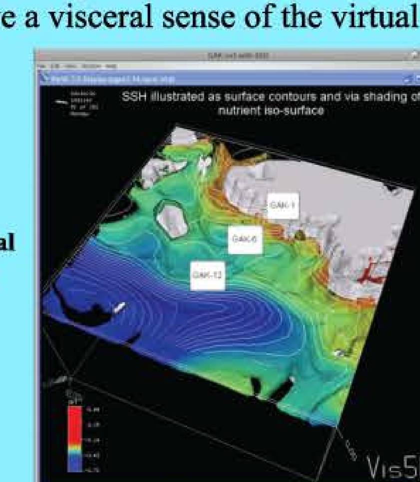


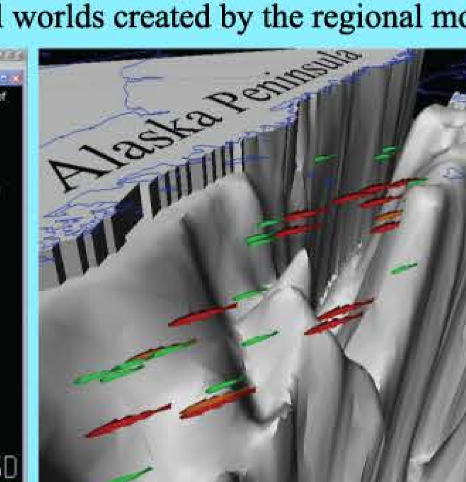
Sample trajectories of "winners" (a) and "losers" (b) from an IBM of Pacific cod.

3D visualization and outreach

A variety of stereo-immersive 3D visualization techniques have been used to display model results, to gain scientific insight and to engage the public. These methods have been deployed at seminars, science fairs, school classrooms and local aquaria, and give a visceral sense of the virtual worlds created by the regional models.

3D biogeochemical model results





3D display of Individual-based model results (fish colored by life stage)

QR code for movie!

3D display with polarized glasses at PMEL seminar

3D display of Bering-10K results at Seattle Aquarium