Theme Session on Intermediate-Scale Physical Processes and their
Influence on the Transport and Food Environment of Fish
CM 1995/Q:18

NEW MODELS FOR THE EXPLORATION OF BIOLOGICAL PROCESSES AT FRONTS

Peter J.S. Franks

Marine Life Research Group, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA

Abstract

The use of models in the exploration of biological processes at fronts has been limited by the poor representation of boundary-layer processes in these models. The strongly sloping pycnocline of frontal regions forces very different buoyancy and momentum fluxes on either side of the front. This cross-frontal contrast in the vertical mixing of heat or momentum by wind or bottom stress couples to the horizontal velocities, creating non-linear cross-frontal flows. These vertical and horizontal motions have immediate impacts on the spatial and temporal patchiness of biological properties at fronts. New model architectures now couple more accurate representations of turbulent mixing in boundary layers with traditional primitive-equation models. Recently, these coupled primitive-equation/mixed-layer models have been integrated with simple ecosystem models to explore the dynamics of biological processes at fronts. I describe two different architectures of these coupled models: a slab mixed-layer/primitive-equation/ecosystem model, and a turbulence-closure mixed-layer/primitive-equation/ecosystem model. These models have been applied to a wind-forced front and a tidal front, respectively. The scales of physical features and biological patchiness described by the models with mixed-layer physics are quite different, usually smaller, than the scales predicted by the primitive-equation models alone. Resolution of vertical processes is significantly enhanced by the inclusion of mixed-layer physics, contributing to a more accurate description of biological dynamics at these intermediate scales.

Introduction

The relatively low recruitment rate of many marine invertebrate and vertebrate species suggests that only a minute fraction of the spawned larvae find sufficient food, avoid predation, and are retained in hospitable locales. Often the mean level of prey is insufficient to sustain the measured larval growth rates, suggesting that the surviving larvae are finding and exploiting patches of food. How these patches form, and how their dynamics relate to the physical environment has been the subject of much study. Unfortunately, technological limitations have made field observations of the patch dynamics difficult. An alternate approach, the formulation of coupled physical-biological models, has been fruitful. However, such models usually trade off between vertical and horizontal resolution, precluding accurate simulation of many important physical and biological dynamics.

As computers become more powerful and cost less, numerical models of oceanographic processes are becoming more detailed. While models used in coupled biological-physical problems usually lag those used in purely physical studies by several years, there are some new model architectures that add a significant level of detail to existing physical-biological models. In particular, several types of model now include separate equations for the mixed-layer dynamics. As will be demonstrated below, the inclusion of mixed-layer dynamics in a fully coupled physical-biological model significantly improves our ability to simulate and understand intermediate-scale biological patchiness and its relation to the physical environment.

Mixed-Layer Models

Oceanographers are usually familiar with the concept of a surface mixed layer, often defined as the depth from the surface over which the density shows little variation (e.g., <0.1 kg m^{-3}). The surface mixed layer is a particular example of a more general class of features called boundary layers. These boundary layers include bottom, atmospheric and planetary boundary layers; the physical dynamics of boundary layers are distinct from those of the interior fluids and are governed by their own mixing rules.

Several types of model have been developed to describe the physics of boundary layers. These models tend to differ in the degree of detail used to model the turbulent fluxes. A first-order model uses prognostic (time evolution) equations for the mean quantities, but parameterizes the

Theme Session on Intermediate-Scale Physical Processes and their
Influence on the Transport and Food Environment of Fish
CM 1995/Q:18

higher-order moments (variance, etc.) in terms of the first-order variables. These models are easily adapted to finite-difference models, and are computationally efficient. They specify the evolution of the mixed-layer depth, usually based on the turbulent kinetic energy budget of the mixed layer, including wind and mean shear forcings. Many of these models have sharp gradients in properties at the base of the mixed layer, although some use local Richardson number dependencies to smooth out unrealistic jumps. Such models are often called slab, or bulk mixed-layer models because they assume the mixed layer to be homogeneous in all properties. An example of such a model is that of Garwood (1977).

A second-order mixed-layer model uses prognostic equations for both the mean and variance of properties, including the turbulent fluxes. An example of this type of model is given by the Mellor and Yamada (1982) level 2.5 turbulence-closure scheme, which uses a diagnostic equation for temperature variance, but a prognostic equation for the variance of turbulent kinetic energy. By including the variance of properties, the second-order turbulence-closure models allow structure in the mixed layer; in particular, they specify time- and space-varying vertical profiles of the vertical eddy diffusivity within the boundary layer. Because of the greater number of prognostic equations that need to be solved, these higher-order turbulence-closure models are more computationally intensive, and more difficult to integrate with higher-dimensional primitive-equation models.

Coupled Models

The mixed-layer models are typically one-dimensional, describing the evolution of properties in a vertical column of fluid. To obtain realistic descriptions of two- and three-dimensional processes, these vertical models must be coupled to higher-dimensional models describing the vertical and horizontal distribution and evolution of the fluid's properties. These models often solve the fully non-linear equations of motion, and are known as primitive-equation models. The method of solving these equations varies, but must be done numerically. The coupling of the models involves specification of how the mixed-layer depth relates to the underlying model grid, how boundary forcings are distributed within the mixed-layer and primitive-equation portions of the model, and how the underlying primitive-equation dynamics

influence the vertical turbulent kinetic energy budget. Examples of issues to be considered are: does the mixed-layer depth have to correspond to a model grid point, or can the mixed layer vary continuously? How does vertical shear driven by the primitive-equation model couple to the mixed-layer model and vice-versa?

Examples

Two examples of coupled mixed-layer/primitive-equation models will be presented below. These two physical models have been coupled to the simple phytoplankton-zooplankton-nutrient ecosystem model of Franks et al. (1986). The first example uses the Garwood (1977) slab mixed-layer model in a study of the effects of wind forcing on phytoplankton production at an oceanic front (Franks and Walstad, in prep.). In the second example, the level 2.5 turbulence-closure model of Mellor and Yamada (1982) is used in the study of the effects of tidal forcing on the planktonic ecosystem of Georges Bank (Franks and Chen, in prep.). In both examples, a comparison is made between identical model runs with the mixed-layer models active and inactive. The examples with inactive mixed-layer models are similar to most two- and three-dimensional coupled physical-biological models in the literature to date.

The biological models were initialized at a steady state representative of summer time conditions. In the slab mixed-layer model, a nutrient gradient was specified across the front, whereas there was no horizontal dependence to the initial condition for the turbulence-closure model. The phytoplankton sank at 1 m d^{-1} in both models.

Slab Mixed Layer

In this model, a simple exponential front in a geostrophic balance was specified for the hydrographic initial condition. The front was forced with a transient wind stress of 0.2 N m^{-2}, with a duration of 1.5 d. The wind excited inertial oscillations of the front, leading to strong vertical and horizontal pumping at the front (Fig. 1). Without a mixed-layer model, the wind stress was trapped in a relatively thin surface layer, leading to a pronounced cross-frontal surface jet and weak vertical velocities. The inclusion of the mixed-layer physics allowed much deeper penetration of the surface wind stress, leading to a deep mixed layer and a weaker surface jet. Differences in the mixed-layer depth across the front enhanced the cross-frontal density gradient,

Theme Session on Intermediate-Scale Physical Processes and their
Influence on the Transport and Food Environment of Fish
CM 1995/Q:18

leading to strong ageostrophic circulations, including oscillating vertical velocities with amplitudes reaching 100 m d^{-1}.

Over the course of the simulation, the phytoplankton developed a subsurface patch at the front, sustained by cross-frontal nutrient fluxes into the euphotic zone. Because of the weak penetration of the wind stress in the case with no mixed-layer physics, the subsurface patch was shallow and elongate, stretching for about 85 km in the cross-frontal direction. The modification of the distribution of turbulent kinetic energy in the case with mixed-layer physics led to the formation of a deeper, more distinct phytoplankton patch. This patch was closely associated with the front, and had a cross-frontal scale of about 40 km. The dynamics underlying the formation of such phytoplankton patches at fronts have been explored by Franks (1992); the dynamics simulated by the case with mixed-layer physics are more consistent with our understanding of the mechanisms underlying such frontal patchiness.

Turbulence-Closure Mixed Layer ·

The turbulence-closure mixed-layer model was configured for a cross-bank transect of Georges Bank, and forced with an M_2 tide at the southern open boundary (right-hand side of Fig. 2). A linear vertical temperature gradient was used for the initial density distribution, with no horizontal dependence. The tidal forcing was gradually ramped up over five tidal cycles; the results of the 25th tidal-averaged fields are shown in Fig. 2. Without the turbulence-closure physics, a thermally well-mixed region develops over the shallow portion of the bank, although the surface waters are also homogenized by the high level of vertical diffusion necessary to satisfy the numerical stability criteria (0.001 m^2 s^{-1}). While the model forms tidal fronts, their structure bears little resemblance to those measured on Georges Bank: the horizontal stratification is too weak, and the vertical structure is incorrect. The phytoplankton develop some horizontal structure, with high values in the surface waters off the bank, and abrupt horizontal gradients in the northern tidal front. The phytoplankton are not vertically homogenized on the bank, contrary to observations, and the spatial patterns are not a good representation of those seen on Georges Bank.

With the turbulence-closure physics included, much more realistic tidal fronts form on the northern and southern flanks of the bank.

The thermal gradients closely match those measured on Georges Bank during the summer months, as do the currents associated with the tidal forcing. Since there is no wind forcing or surface heat flux, all the turbulence is generated by the friction of the tidal currents over the bottom. This upward mixing led to a well-mixed region on top of the bank separated from the offshore waters by surface-to-bottom tidal fronts. Tidally rectified flows led to strong cross-frontal circulation cells within the fronts. The phytoplankton patterns were very different from the simulation without the mixed-layer physics, and agreed both quantitatively and qualitatively with patterns observed on Georges Bank. A subsurface chlorophyll maximum in the offshore waters was separated from the well-mixed region on the top of the bank by regions of enhanced biomass, particularly on the northern flank. The distinct patch within the northern front was supported by nutrients advected and diffused from below. This mixing was very isolated in time and space; the bulk of the mixing occurred during a 2 h period near the flood-to-ebb transition, in a region only 5 km wide. The shape of the phytoplankton patch changed radically over a tidal cycle, as it was advected downward in the cross-frontal circulation cell during the flood tide.

Conclusions

The two examples presented above clearly demonstrate the utility of coupled mixed-layer/primitive-equation/ecosystem models in simulating the formation of biological patchiness in response to physical forcings. Without the mixed-layer physics, the models did a poor job of describing the physical and biological patchiness: the inaccurate description of the transport of momentum from the boundaries led to over estimation of the phytoplanktonic patch scales, and an inaccurate simulation of their relationship to the physical dynamics. Inclusion of the mixed-layer models tended to increase the amount of biological patchiness, and to decrease the scale of the patchiness. Strong temporal and spatial variability of the patchiness became evident, and the relationship of the patches to the underlying physics could be studied.

These studies have examined only the two-dimensional behaviour of coupled mixed-layer/primitive-equation models. The inclusion of along-front variability will add a further degree of patchiness, created by frontal meanders and instabilities. These patches will have strong local influences on the mixed-layer dynamics

Theme Session on Intermediate-Scale Physical Processes and their
Influence on the Transport and Food Environment of Fish
CM 1995/Q:18

and vertical distribution of turbulent kinetic energy. To understand the relationship of biological and physical dynamics in these regions, we must accurately describe the boundary-layer physics and their coupling to the larger-scale flows. Such studies should help us understand the influences of biological and physical patchiness on fish feeding and aggregation in the world's oceans.

References

P. Franks, Marine Life Research Group, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA 92093-0218. (e-mail: pfranks@ucsd.edu)

Franks, P.J.S., Phytoplankton blooms at fronts: patterns, scales and physical forcings, *Rev. Aquat. Sci., 6*, 121-137, 1992.

Franks, P.J.S. and C. Chen, Plankton production in tidal fronts: a model of Georges Bank in summer, *in prep.*

Franks, P.J.S. and L.J. Walstad, Phytoplankton patches at fronts: a model of formation and response to wind events, *in prep.*

Franks, P.J.S., J.S. Wroblewski and G.R. Flierl, Behavior of a simple plankton model with food-level acclimation by herbivores, *Mar. Biol., 91*, 121-129, 1986.

Garwood, R.W., Jr., An oceanic mixed layer model capable of simulating cyclic states, *J. Phys. Oceanogr., 7*, 455-468, 1977.

Mellor, G.L. and T. Yamada, Development of a turbulent closure model for geophysical fluid problems, *Rev. Geophys. Space Phys., 20*, 851-875, 1982.
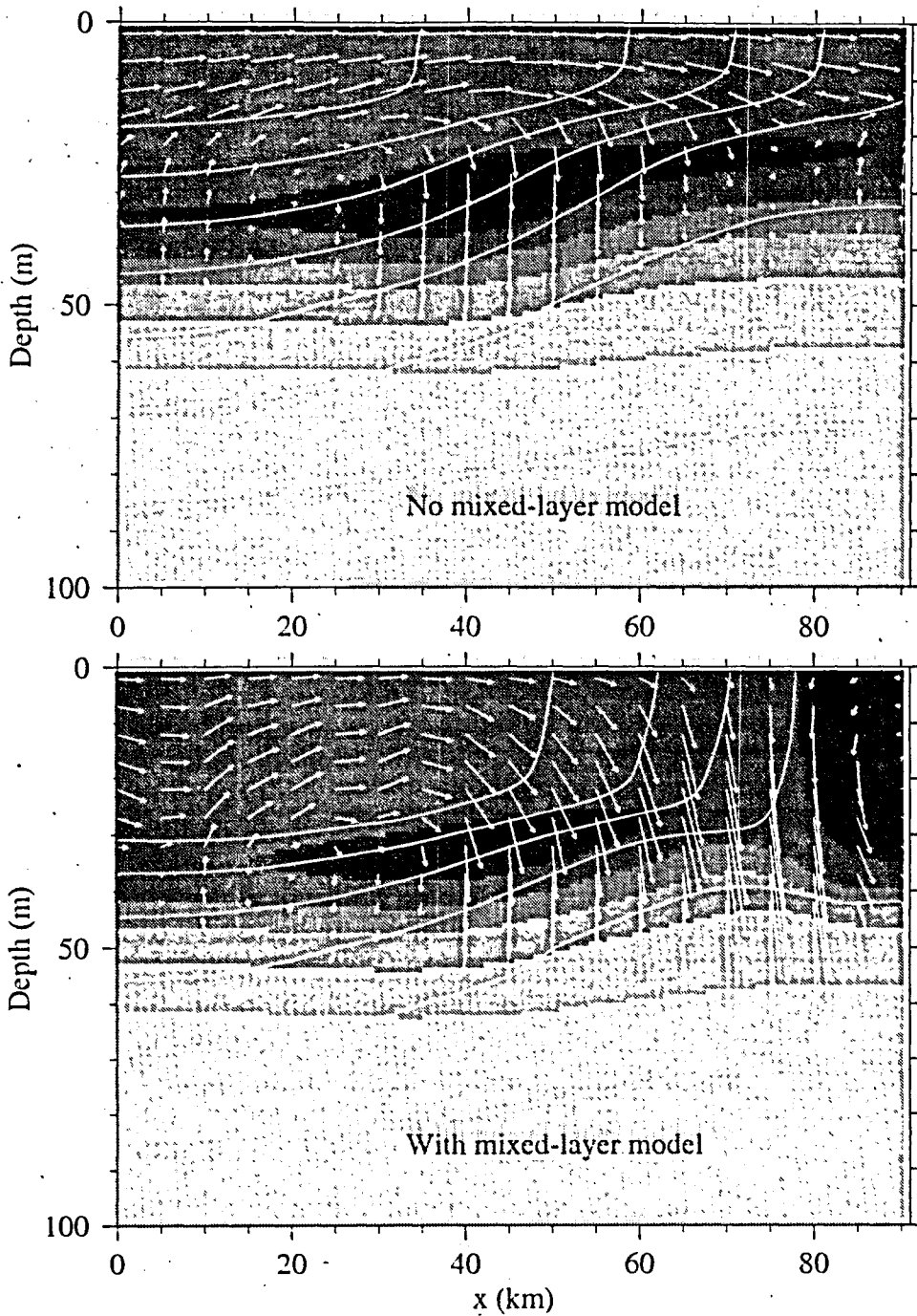
Fig. 1. Slab mixed-layer/primitive-equation/ecosystem model of an oceanic front.
Top panel: without mixed-layer dynamics. Bottom panel: with mixed-layer
dynamics. White contours are isotherms (1 °C), white arrows indicate cross-
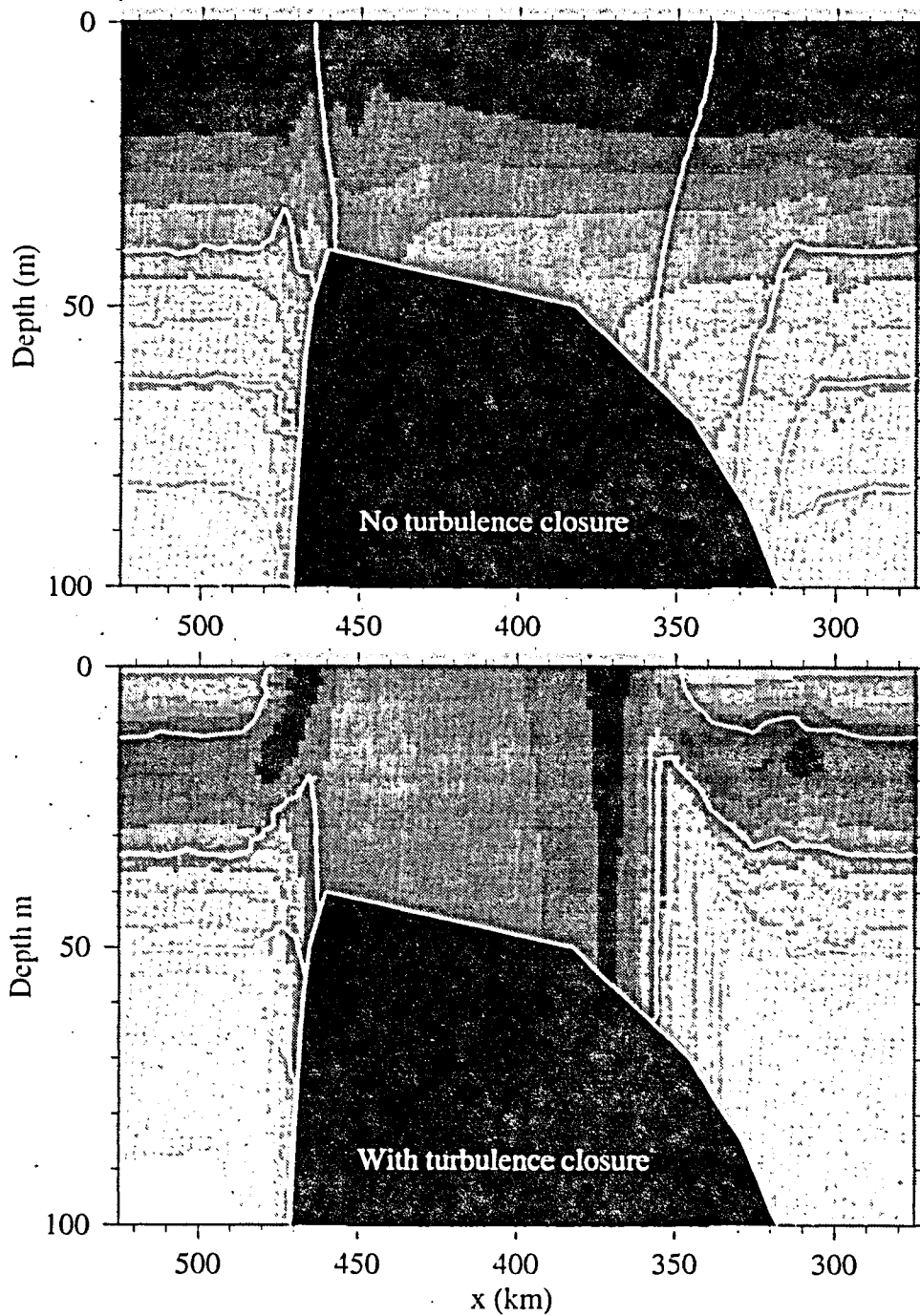frontal velocities, grey scale is phytoplankton biomass (black: max, white: min).

Fig. 2. Turbulence-closure/primitive-equation/ecosystem model of Georges Bank.
Top panel: without turbulence-closure dynamics. Bottom panel: with turbulence-
closure dynamics. Black area indicates cross-section of bank. White contours are
isotherms (1 °C), grey scale is phytoplankton biomass (black: max, white: min).