# Near-Boundary Processes and Their Parameterization

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We think of the ocean as being driven by a variety of forces: tides, wind, surface buoyancy fluxes associated with heating, cooling, evaporation, precipitation and ice formation, and geothermal heating. Apart from tidal forces, which act throughout the ocean, geothermal plumes that rise far into the ocean interior, and locations of deep convection, these driving forces communicate their influence to the ocean via boundary layers that are thin compared to the ocean depth. In a sense, therefore, the behavior of the ocean is controlled by what happens in these boundary layers. The response of the boundary layers to forcing sets boundary conditions of fluid injection or removal that force a response in the rest of the ocean. We are familiar, for example, with the role of "Ekman suction" as the means by which the wind drives ocean circulation.

Quite apart from these dynamical considerations, we also recognize that gas exchange with the atmosphere can only influence the bulk of the ocean after it has passed through the surface boundary layer. Similarly, sedimentary and biochemical processes at the seafloor involve the bottom boundary layer of the ocean and only affect the ocean interior through exchange between it and the boundary layer. Quantifying these exchanges clearly requires a thorough understanding of the nature and behavior of the boundary layer or, to be more general and avoiding for now a definition of what is meant by "boundary layer," we could refer to the "near-boundary" region.

Some of the influence of the driving forces is more subtle in that it involves the radiation into the ocean interior of internal waves that carry with them both momentum and the energy that can lead to turbulence and mixing elsewhere. Quantifying these effects again requires a detailed understanding of the near-boundary region. For example, a very simple model of the energy flux associated with wind-driven internal waves shows that it depends on the thickness of a surface homogeneous layer.

The Thirteenth 'Aha Huliko'a Hawaiian Winter Workshop was convened from 21 to 24 January 2003 to review the general theme of "Near-Boundary Processes and Their Parameterization," with the support of the Office of Naval Research and the participation of 25 invited speakers. The emphasis was on the physics of the regions of the ocean near the surface, the bottom, and the sloping sides, with full recognition that predictive models for ocean behavior require that the effects of small-scale, near-boundary processes be "parameterized," i.e., represented by formulae in terms of model variables rather than just expressed as numbers that might be correct only for particular conditions.

Large-scale numerical modelers are, of course, trying their best to include more appropriate parameterizations into their models but they face substantial barriers. Their models might not resolve the variables that the parameterizations require. Numerical errors might overwhelm the physical effects. Indeed, well-known effects like numerical diffusion, numerical entrainment, and spurious diapycnal mixing become aggravated near boundaries when topographic and isopycnal slopes become large and when boundary layers and overflows become thinner than the typical vertical grid spacing. Considerable work is underway to design numerical algorithms that keep these numerical effects in check and allow physics to rule, but these efforts were only reviewed in passing.

The workshop also did not deal directly with important issues of sediment transport, gas transfer, or biogeochemical processes, but we hope that the report helps to establish the physical framework within which these issues are considered. In fact, we did not even focus extensively on the details of the boundary layers themselves. Instead, emphasis was placed on their interaction with the ocean interior, recognizing that this is a two-way process: near-boundary regions influence the ocean interior but are also themselves affected by the properties of the interior.

The report that follows only gives a broad summary of the meeting and a few references. More details and references can be found in the workshop proceedings which are available from www.soest.hawaii.edu/PubServices/AhaHulikoa.html.

## General Considerations

For a model that resolved the smallest scales of fluid motion, perhaps only a millimeter or so, the boundary conditions would be simple. At a solid

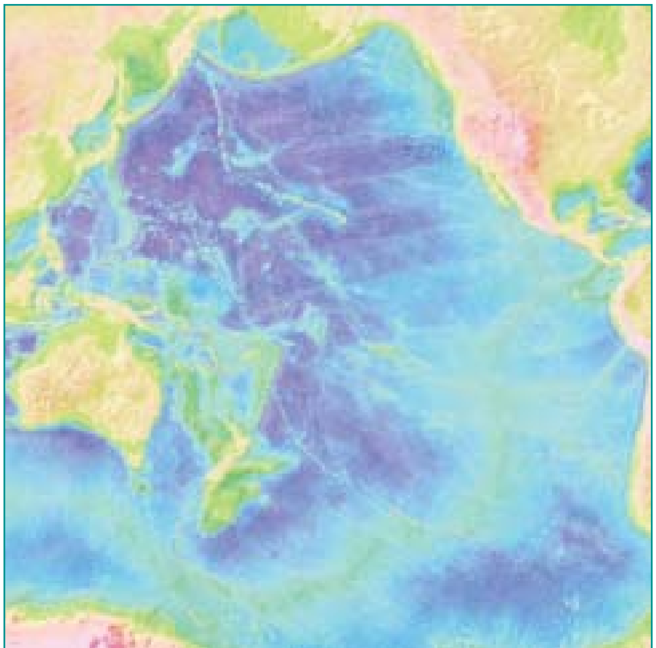

*Figure 1. A map showing the varieties of topographic terrains including abyssal plains, continental shelves and slopes, mid-ocean ridges, seamounts, canyons etc, in the Pacific Ocean. Such variety continues on smaller scales not resolved by the 2′ longitude and 1.36′ latitude resolution of the Smith and Sandwell topography (see http://www.ngdc.noaa.gov/mgg/image/seafloor.html) shown here, down to the smallest scales such as sand ripples.*

boundary there would be no velocity at right angles to the surface, a no-slip condition for the tangential velocity, and flux conditions for scalars that would involve only molecular diffusion coefficients. At the moving sea surface the situation would be more complicated, but in principle everything is defined.

Recognizing the limitations of resolution of any realistic model, the next step might be the assumption that the boundary layer at the sea floor obeys the "law of the wall," with a logarithmic velocity profile and a drag that could be expressed in magnitude as $C_d u^2$, where $u$ is the flow speed at some prescribed height and $C_d$ a drag coefficient that depends on the bottom roughness. Assuming the logarithmic layer to be of infinitesimal thickness, one thus has a bottom boundary condition for the rest of the ocean. To be sure, some of this might also be turbulent and require process parameterization, but with much less resolution required than if the log layer were treated explicitly. Similarly, the surface of the ocean might be assumed to be forced by a wind stress expressed in terms of the wind speed at some height, though the response of the ocean just below the surface is no longer a simple log layer, but is complicated by the effects of wave breaking which has a major influence on turbulence levels and gas exchange.

At both the seafloor and the ocean surface, the stress might be distributed over a turbulent region of finite thickness. In the presence of Earth's rotation, the response should have some of the characteristics of the classical Ekman layer. This, rather than the embedded log layer, might then be taken as the unresolved boundary layer, with the bulk of the ocean driven by Ekman convergence and divergence forcing fluid into or out of the interior.

The situation becomes more complicated as soon as one adds effects such as ocean stratification. The temperature and salt transported by the Ekman flux, either at the surface or sea floor, depend on how far the Ekman layer extends beyond a mixed layer into the stratified region. An additional effect at the seafloor is that the presence of a bottom slope may cause the Ekman layer to be "arrested" by buoyancy forces, and large topographic features introduce further complications. It clearly becomes difficult even to decide what one will regard as a boundary layer to be parameterized and what one will try to treat explicitly in a model for the ocean interior.

The parameterization of boundary layers is further complicated by the presence of mesoscale eddies. If these are also unresolved, as is still the case in climate models, their effect on, and interaction with, surface and bottom boundary layers will need to be parameterized.

Understanding and parameterizing near-boundary regions is an immense and complicated, but fascinating, task. The rest of this report will touch on many of the questions, particularly those addressed at the workshop. The next two sections will focus on some details of the bottom and surface regions, but we then return to more general questions of parameterization philosophy and also discuss how the community can bridge the gap between those who delight in unraveling the detailed physics of ocean processes and those who revel in the grand scales of general circulation models.

## The Near-Bottom Region

While parts of the seafloor, such as abyssal plains, are as flat and smooth as in a modeler's dream, regions with a significant slope and bottom roughness are extensive and need to be considered (Figure 1).

The variety of topographies immediately raises the question as to what topographic scales matter, for the properties of the boundary layer itself, for communication with the interior, and for the radiation into the interior of momentum- and energy-carrying internal waves, but there are many other issues, too. A cartoon of the near-bottom region and the processes there is given in Figure 2.

### *The Boundary Layer*

Even over flat and smooth abyssal plains, there are interesting questions that are still unsettled. Is the thickness of a well-mixed boundary layer determined just by the mean flow and stratification in the interior ocean? Does the Ekman flux involve part of, all of, or more than this thickness?

If the bottom topography is rough, one presumes that a simple, well-mixed boundary layer is not greatly affected by "roughness elements" which have a height much less than the boundary layer thickness, except insofar as they act as stirring rods to increase the level of turbulence and perhaps thicken the layer. But what is the role of small seamounts that penetrate the interface between the boundary layer and the interior? It is clear that the actual height of features matters, not just the spectrum of bottom roughness.

*…insufficient attention has been paid to the effects of the ridges and canyons that are usually associated with mean slopes.*

In the presence of a mean slope, buoyancy forces act on an Ekman layer which moves fluid up or down the slope, modifying the transport. Complementary to this, mixing near a boundary distorts mean-density surfaces, leading to further mean flows. These phenomena have been discussed extensively in the literature for a uniform slope (e.g., Garrett et al., 1993), but insufficient attention has been paid to the effects of the ridges and canyons that are usually associated with mean slopes. In particular, it seems that in some locations the strongest mixing occurs within the canyons that cross steep slopes (St. Laurent et al., 2001).

### *Overflows*

Overflows, currents of dense water that flow over sills or through fracture zones from one ocean basin to another, are a topic of particular interest as they control interbasin exchange and are also often regions of intense mixing caused by the flow itself (e.g., Ferron et al., 1998). Indeed, overflow mixing has been suggested as a major contributor to deep ocean mixing and water mass modification, along with boundary and interior mixing driven by tidally or wind-generated internal waves.

Treating overflows correctly in numerical ocean circulation models is particularly problematic if rectangular grids are used, as these grids do not adequately resolve the overflow scales. Dense water leaving a cell adjacent to the boundary may find itself above a cell with less dense water and mix over a larger scale than is appropriate. Parameterization schemes that treat overflows separately are being explored, but there are major uncertainties about appropriate representations of entrainment of ambient fluid into the overflows, or detrainment from the overflows into the ocean interior. At the same time, grids are being developed that adapt to the topography and do not lead to spurious mixing.

### *Communication with the Interior*

It is a standard expectation that currents in the ocean interior with frequencies much less than the Coriolis frequency will lead to an Ekman flux in the frictionally influenced boundary layer near a solid boundary, and that convergence or divergence of this flux will have a back effect on the interior currents. As has already been pointed out, the situation becomes more complicated near a sloping boundary where upwelling or downwelling Ekman flows can be arrested by buoyancy forces, but our understanding of the basic physics is adequate for the proposal of reasonable parameterization schemes. We are much less able to deal easily with situations where the flow separates at topographic features, thus directly advecting fluid from the near-boundary region into the interior.

It has also long been recognized that mixing tends to be enhanced near sloping and rough topography, and that this too, can lead to exchange with the interior. It is sometimes suggested that near-boundary mixing might just mix fluid that is already mixed and be ineffective in providing a vertical buoyancy flux in the

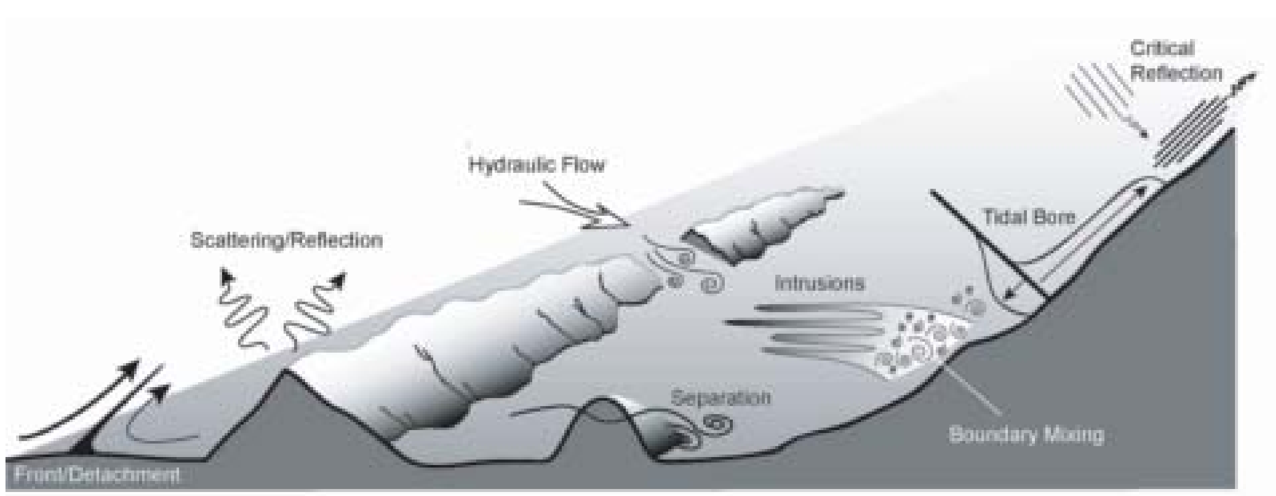


***Figure 2.*** *A cartoon of processes occurring near the seafloor.*

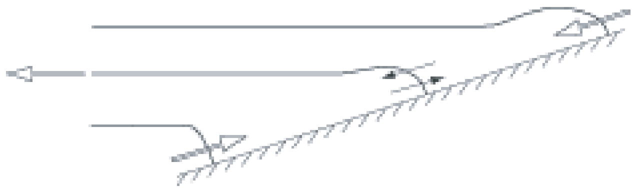

***Figure 3.*** *Flows driven by mixing near a plane-slope boundary for a fluid with variable interior stratification. The lines represent isopycnal surfaces, distorted by mixing near the slope. This distortion leads to density-driven restratification with both upslope and downslope "secondary" flows, as shown for the middle isopycnal. If the stratification in the interior is enhanced at this level, the spreading of the isopycnals near the slope will lead to a convergent "tertiary" flow, as shown for the outer two isopycnals here, and a flow into the ocean interior.*

ocean, and thus that there is a need to sweep away the mixed fluid and replace it with stratified fluid. This may indeed occur, particularly if there is a mean flow moving stratified fluid past isolated mixing agents such as seamounts, but it is not necessary. Mixing near a sloping boundary will distort isopycnals away from the horizontal, so that there is a tendency for buoyancy forces to drive restratification *in situ* (Figure 3). For a uniform slope and interior stratification, a vertical buoyancy flux can be maintained in the boundary layer without any exchange with the interior. Such an exchange will occur, though, if there is a vertical gradient in, for example, the interior ocean stratification. In such a case, partially mixed fluid will be extruded from the boundary layer into regions of high stratification, spreading the isopycnals there (Figure 3). The current away from the slope will be influenced by the Coriolis force and might come into geostrophic balance, but then undergo an instability leading to eddies which transport fluid away from the boundary. Within canyons, of course, the Coriolis force on the extruding flow can be balanced directly by a pressure gradient.

Whether such a scenario actually occurs is uncertain, but it does illustrate the complexity of processes. Even the basic boundary layer on a slope may be susceptible to the formation of small-scale intrusions (McPhee-Shaw and Kunze, 2002). It is not clear whether these need to be treated explicitly or can be subsumed into some parameterization of mixing near the slope.

In practice, much of the strong mixing near sloping and rough topography extends a considerable distance from the slope (e.g., Ledwell et al., 2000) into water that has much the same stratification as that farther out where the mixing is less. Theories for this situation give results that are sensitive to the "eddy Prandtl number," the ratio of mixing coefficients for momentum and buoyancy, thus drawing attention to the need for more investigation of the eddy flux of momentum near boundaries. This is part of the general problem of internal wave radiation from boundary regions, to be discussed next.

### *Radiation and Scattering*

It is increasingly thought that a considerable amount of the mixing that occurs in the ocean, particularly the abyssal ocean, is caused by internal tides. These are the internal waves of tidal frequency that are generated as the main tidal currents in the ocean sweep stratified water over topographic features on the seafloor. There are a number of different regimes, determined by factors such as the bottom steepness compared with the slope of rays of internal tide energy and the distance that water parcels travel with the tides compared with the length scale of the bottom features.

It seems that, while some of the internal tide energy flux leads to local near-boundary mixing, and this mixing may be much greater than ambient values in the ocean interior, most of the flux is in low modes with large vertical scales and little likelihood of causing immediate mixing close to the generation region.The emphasis here is on the word "immediate," the radiated energy will be reflected from the sea surface and re-encounter the sea floor within O(100) km of its generation site. This encounter, and even further "bounces," may well still be within an extensive region of rough topography (such as the Mid-Atlantic Ridge), leading to further scattering into high modes (much akin to the initial generation situation) with local breakdown into near-boundary turbulence and mixing. For more isolated topographic features, such as the Hawaiian Ridge, the low mode energy travels far away, possibly breaking as "internal surf" on distant continental slopes.

A general problem is, therefore, to determine the extent and profiles of internal tide mixing near boundaries, either near the generation site or far from it, as well as having the radiated energy feed a gradual breakdown into smaller scale waves, instabilities, and mixing in the ocean interior. Simple calculations and numerical models do suggest that ocean circulation is sensitive to the spatial distribution of mixing and not just its average value at a particular depth or on a particular mean isopycnal surface (e.g., Marotzke, 1997).

Progress will come from combining local process studies with global studies such as the ones shown in the bottom panel of Figure 4. Estimates of the surface to internal tide conversion rate (estimated from the residual of a global tidal model into which TOPEX/Poseidon altimeter data have been assimilated) have areas consistent with depth-integrated horizontal energy fluxes in the internal tidal band (estimated from moored current meter records). The upper panel of Figure 4 shows a similar estimate for wind-generated near-inertial internal waves, to be discussed further below.

The tidal currents near the seafloor are generally larger than currents associated with low-frequency currents and eddies, but there are locations, such as

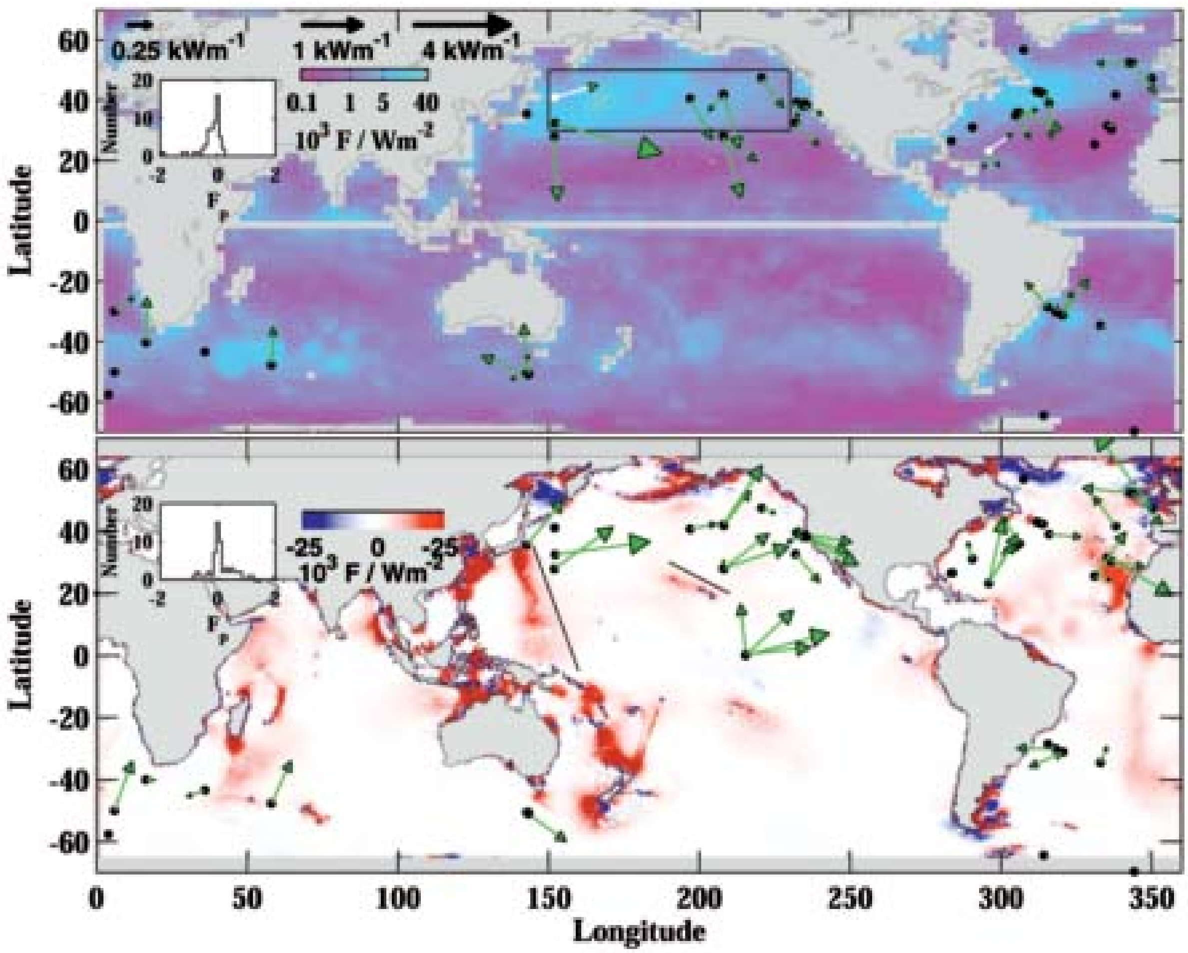


*Figure 4. Source terms and energy-flux vectors.* ***Top:*** *Depth-integrated, annual-mean, near-inertial energy-flux vectors for modes 1 and 2 from 60 historical moored records. The arrow lengths are logarithmic, with references indicated at the upper left. Moorings with |F| < 0.1 kW m*$^{-1}$ *appear as black dots without an arrow. The few instances of poleward propagation are plotted in white. The color map represents annual-mean energy input from the wind to simulated near-inertial mixed-layer motions. The color scale is logarithmic and is indicated at the upper left.* ***Bottom:*** *The same energy-flux vectors but for the semi-diurnal tidal band. The color map represents the surface to internal tide conversion rate estimated from a tidal model into which TOPEX/Poseidon altimeter data have been assimilated. (Courtesy of G. D. Egbert.) The insets show histograms of the poleward flux component for all moorings. (Courtesy of M. Alford.)*

parts of the Southern Ocean, where the latter are strong and can be expected to generate significant lee waves as they flow past sea floor topography. The magnitude of these waves will depend on various factors including the heights of features, compared with the thickness of a well-mixed bottom boundary layer, and their widths (Figure 5).

It is important to recognize that these internal waves generated at the seafloor will carry momentum as well as energy into the ocean interior. The influence and correct parameterization of this momentum transport are much less well understood in the ocean than in the atmosphere where it is of great importance. In general, of course, particularly near boundaries, we do not know whether momentum exchange is governed more by internal waves or by "vortical modes" generated as flow separates and generates eddies near sharp topographic features. This flow separation is certainly a key phenomenon in the coastal ocean (Figure 6). In general, the divergence of the momentum transport by various processes near rough topography needs more attention.

## The Near-Surface Region

The near-surface region is no easier to treat than the region near the seafloor. Although the surface is flat (apart from small-scale surface waves), without the complications of seafloor topography, there is a rich array of additional physical phenomena to be investigated (Figure 7), particularly those associated with

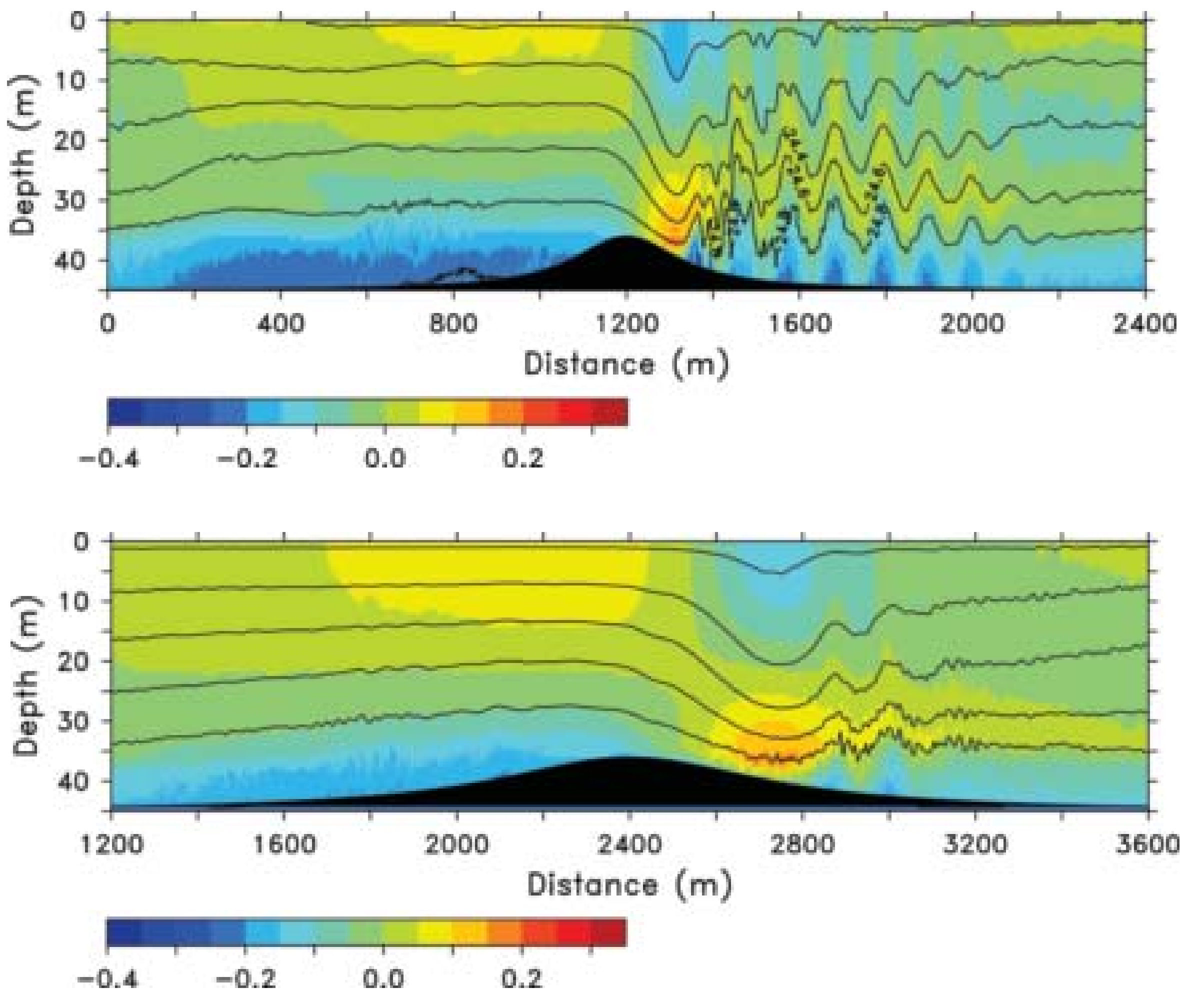


*Figure 5. Large-eddy simulation of lee wave generation by flow past bottom obstacles. Shown are vertical cross sections of velocity (color code) and density (contours). The two panels compare an obstacle 150 m wide* ***(top)*** *in a channel 2400 m long and an obstacle 325 m wide* ***(bottom)*** *in a channel 4800 m long (only the middle half is shown). In both cases the obstacle height is 9 m, the flow speed 0.2 m $s^{-1}$, and the stratification 0.015 $s^{-1}$ (Courtesy of E. Skyllingstad and H. Wijesekera.)*

air-sea interaction and surface waves. For a start, the mixing processes now include breaking waves and Langmuir circulation as well as turbulence generated by shear flow instability.

### *The Boundary Layer*

Even if the surface boundary layer is dominated by local processes, with a one-dimensional approach being appropriate, there are many effects that are not fully resolved, either by observations or by models. Measurements of turbulent velocities with neutrally buoyant floats clearly show that the oceanic surface layer is different from solid-wall turbulent boundary layers, perhaps as a consequence of breaking waves, Langmuir circulation, and bubble subduction. These phenomena were not reviewed at the workshop but their role can and should be resolved through a comparison of data and process models. There was, however, discussion of the region immediately below the base of the homogeneous surface layer. It seems that some of the momentum imparted by the surface wind stress penetrates into this region (Figure 8), with consequences for the water that is transported in the Ekman layer, but the mechanisms are not fully understood.

It also is important to recognize that the output of some mixed-layer models is sensitive to the "background diffusivity" used below the base of a well-mixed surface layer, but we are a long way from being able to prescribe vertical profiles of an eddy viscosity and eddy diffusivity in terms of large-scale variables, or even deciding whether such a parameterization is appropriate.

Another interesting issue is that in many locations it is inappropriate to ignore the effect of lateral

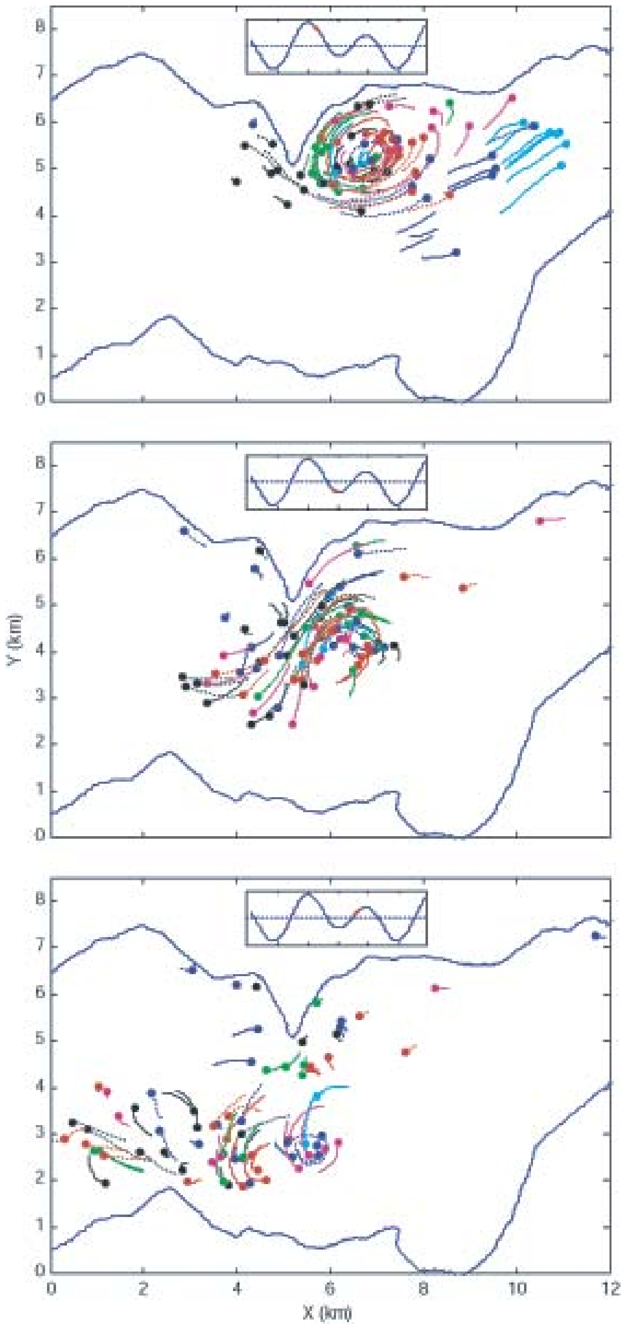


*Figure 6. Observed drifter tracks at 20 m depth for 2, 6, and 10 hours after the time of maximum flood current at the Three Tree Point headland in Puget Sound. Colors represent individual drifter releases (on different days). Circles indicate concurrent drifter locations with the tails representing 90-minute paths. Flow separation is evident, as is the "headland eddy" and its evolution and breakdown by which fluid is stirred away from the headland. (Courtesy of G. Pawlak, P. MacCready and R. McCabe.)*

gradients. For example, in frontal regions a significant amount of restratification of the surface mixed layer can be driven by the buoyancy forces associated with horizontal density gradients.

### Communication with the Interior

The simplest view is that the exchange between the surface boundary layer and the ocean interior is just a matter of convergence and divergence of the wind-driven surface Ekman layer. Quite apart from the issue, raised above, of the actual thickness and content of the Ekman layer, we also have to allow for geostrophic flow in the upper ocean and for the effects of mesoscale eddies. In particular, baroclinic instability of a lateral density gradient can lead to an effective adiabatic relaxation of isopycnal slopes in the ocean interior, leading to a lateral diabatic flow in the surface mixed layer. As well as causing this mean advection, the mesoscale eddies cause lateral mixing at a rate that appears to be significant. A number of aspects of these process are not understood, however. What is the relationship between the advection and lateral mixing caused by the eddies? What are the correct parameterizations and how do they depend on a buoyancy jump at the base of the surface mixed layer? What ultimately happens to the potential energy that is transferred from the mean flow to the eddies?

It is also important that dynamical estimates of lateral fluxes be compatible with thermodynamic considerations. For example, if warm water is moving poleward as a consequence of the Ekman flux and eddy processes, is it losing heat at a rate compatible with the poleward temperature gradient?

### Radiation

The internal wave field in the ocean interior is partly fed by internal tides generated at the seafloor, and partly by internal waves generated by the wind. Although some of these waves may be high frequency, it is thought that most of the energy goes into near-inertial waves. These have a frequency close to the local Coriolis frequency and arise from the adjustment of surface currents left behind by fast-moving storms. The magnitude of these currents, and hence the energy flux into the interior, is a function of the surface layer thickness, providing for one way in which the internal waves depend on the surface layer. Another arises because it seems that not all the inertial wave energy flux escapes the near surface region (e.g., D'Asaro, 1995), perhaps partly as a consequence of the interaction of the inertial waves with low frequency currents. The energy lost from the waves may contribute to the mixing below the mixed layer base that was mentioned earlier. Overall, in fact, the interaction between internal waves and the surface mixed layer needs more attention. One effect is that the heaving of the base of the layer by internal waves can modify the deepening behavior and hence the average thickness and properties of the layer. In some situations, it seems that internal tides propagating upwards from the seafloor can cause observable effects and mixing near the surface, even steepening to produce highly nonlinear "internal solitons." The overall importance of this

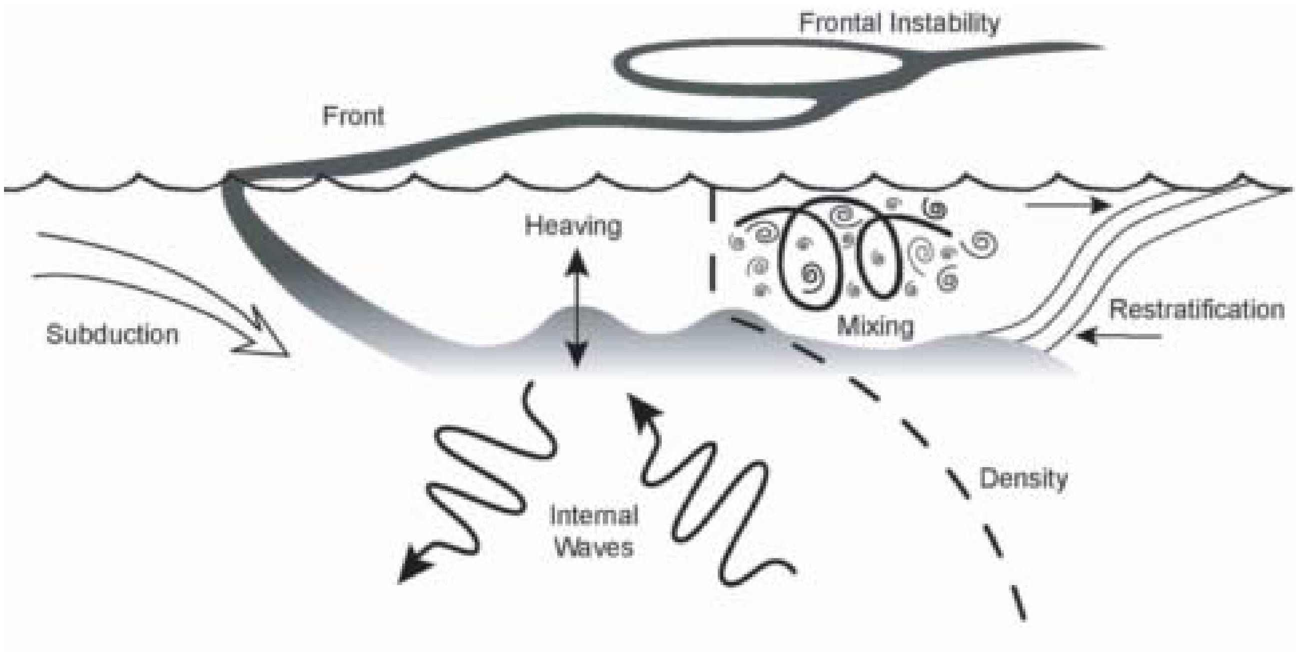


***Figure 7.*** *A cartoon of processes occurring near the sea surface.*

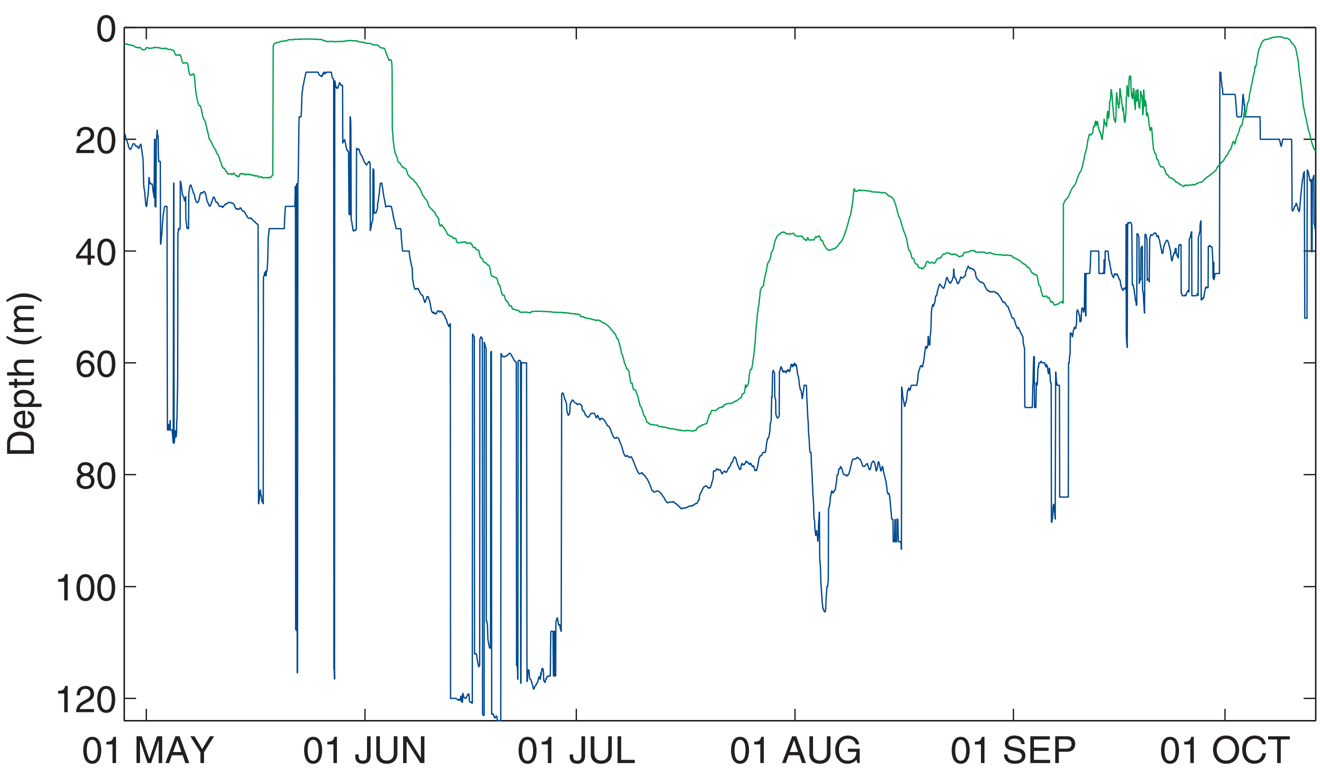


***Figure 8.*** *Penetration of wind-driven momentum during the SW Arabian Sea monsoon. The penetration depth of the wind-driven flow (blue curve, defined as the depth at which the transport measured by a moored Acoustic Doppler Current Profiler equals the theoretical Ekman transport) is correlated with, but consistently exceeds, the mixed-layer depth (green curve, measured by a 0.1°C difference from the surface) by roughly 20 m. (Courtesy of D. Rudnick.)*

is not understood. There are clearly many feedbacks among the well-mixed surface layer, the internal wave field, and the near-surface region below the base of the well-mixed layer. We shall return to this later.

While internal tides may be affected by the near-surface region of the ocean, a more important process is likely to be the interaction between internal waves and a sloping or rough seafloor. Reflection and scattering into higher modes add to the mixing in the abyssal ocean, with questions as before about the importance of this process compared with wave-wave interactions, instabilities, and mixing in the ocean interior far from the boundaries. Again, local process studies need to be complemented by global assessments, as illustrated by the top panel of Figure 4. This panel shows the energy input from the wind to near-inertial mixed-layer motions (estimated from the wind field) and depth-integrated horizontal energy fluxes in the near-inertial band (estimated from moored current meter records).

## Parameterization

So far we have largely discussed a rather bewildering collection of near-boundary processes. We have already pointed out the impossibility of large-scale models resolving phenomena at the smallest scale of motion, just a matter of millimeters, but serious discussion of the choice between resolution and parameterization is required when it comes to motions of intermediate scale such as mesoscale eddies, the boundary layers themselves, and features such as overflows. It does seem that one should think in terms of future, rather than present, computer power, and, indeed, one hopes that mesoscale eddies will be resolvable before too much longer. This mesoscale resolution might even be necessary, given the difficulty in proposing accurate, universally applicable, parameterizations of these eddies.

For boundary layers and overflows, the general consensus is that devoting computational resources to increasing resolution within a large model might not be the most effective way to proceed. The reason is that models which resolve small-scale boundary layers and overflows will inevitably be restricted to rather simple parameterizations of the processes that are still unresolved. It seems more satisfactory to have separate, but coupled, models for the boundary regions and the ocean interior. This raises questions, of course, about where the dividing line will be between the two. It seems likely, for example, that one would extract the well-mixed boundary layers, but still allow for the representation, in the interior model, of many near-boundary processes.

The models for the boundary layers will, of course, have to be efficient as well as appropriate; resources are not adequate to run, say, a detailed Large Eddy Simulation (LES) of the surface mixed layer in parallel with a general circulation model of the ocean interior. The LES studies will have to be condensed into parameterizations that optimize some combination of accuracy, ease of use, and efficiency.

This needed optimization, in fact, raises a key issue that may not be sufficiently appreciated in the oceanographic community, though well recognized by modelers of the global atmospheric circulation: many small-scale processes are reasonably well understood, but a precise calculation and representation of their effects is too cumbersome for ready use in large-scale models. An atmospheric example concerns the momentum flux associated with internal lee waves generated by flow over hills and mountains. General formulae for this flux have needed to be reduced to simple forms involving average features of the topography. This, and equivalent tasks for the ocean, are far from trivial.

The value is also recognized of sensitivity tests in which proposed parameterizations are introduced into large-scale models and their importance assessed, leading to feedback on which processes need more detailed investigation and more accurate representation.

Less obvious, perhaps, is the need for numerical investigations of idealized situations. One such study shows how the internal tide cascades energy to lower frequencies and higher vertical wavenumbers at low latitudes but not at mid-latitudes. This result reinforces suggestions of the importance of a mechanism known as Parametric Subharmonic Instability which transfers energy to internal waves of half the initial frequency, provided that this new frequency is greater than the local Coriolis frequency. Such investigations are useful first steps in the development of a global internal wave model that will combine generation, propagation, evolution, and dissipation of the waves, leading to appropriate representation of mixing in models.

## How Do We Do This?

The complexity of small-scale processes in the ocean makes it difficult for one person to have a complete overview of the present understanding of these processes and of model requirements and sensitivities. It is also difficult for one person to be confident in the identification of processes and regions where new observations are required. To some extent this uncertainty makes it more likely that research will continue on a broad range of topics, thus avoiding the risk associated with putting too many eggs in the one basket identified by a committee; the key studies might well, as has happened in the past, turn out to be different from those anticipated. On the other hand, some planning and discussion of priorities is desirable. The Climate Process Teams initiated under the auspices of CLIVAR are a promising initiative, with one team bringing together a mix of those who study small-scale processes and those who run large ocean circulation models (see www.usclivar.org/CPT/Ocean_mixing_whitepaper.pdf).

It also seems that, as in the atmospheric community, there will be an increasing number of jobs for individuals prepared to bring the results of process studies to the modeling community. As discussed earlier, this is a challenging task.

## Conclusions

Near-boundary processes determine the response of the ocean interior to most of its driving forces. They thus impact the ocean's circulation, its property distribution, its variability, the fate of tracers, the ocean's role in climate, biological productivity and many other aspects. Near-boundary processes are also critical in many coastal and local problems, such as waste disposal, and, of course, in lakes as well as the sea. There are thus many practical reasons for their investigation, with a view to parameterization in large models but also for their own sake as part of the human pursuit of an understanding of the natural world.

The difficult task is in choosing priorities, and it would be an exaggeration to say that a clear list of these emerged from the workshop. However, a list of some emergent themes, in no particular order, would include recognition of

- the heterogeneity of boundaries and processes there, making sampling and parameterization difficult,
- the value of numerical studies of processes,
- the value of transforming process understanding into usable and efficient but accurate parameterizations,
- the importance of verifying proposed parameterizations by direct measurement of eddy fluxes rather than just by appealing to circumstantial evidence that a scheme "seems to work"!

Particular questions concerning poorly understood and important processes where observational and theoretical investigation would be fruitful include these:

- what are the mechanisms of exchange between bottom boundary layers and the ocean interior - does restratification occur *in situ* or by vigorous exchange?
- what is the eddy momentum flux near boundaries and what processes are responsible for it?
- what is happening in canyons and abyssal channels, and what is the role of small-scale topographic features within them?
- what processes determine the behavior of the region below the base of the surface mixed layer?

In the meantime, there is no doubt that parameterization schemes used in ocean circulation models can be improved using knowledge we already have, and sensitivity tests using these schemes will lead to refinement of the priorities for future research on processes.

## Acknowledgments

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