Circulation, Exchange and Mixing at the Ocean-Shelf Boundary

J.M. Huthnance

Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside L43 7RA, UK

Abstract. The coastal ocean meets the deep sea at the continental shelf edge. Steep bathymetry may inhibit ocean-shelf exchange, but in combination with stratification gives rise to special processes and modelling challenges. A preliminary assessment is made of potentially influential processes in ocean-shelf exchange, water-mass structure and general circulation, according to their scales and context: internal tides and waves; upwelling, fronts and filaments; downwelling, cascading; along-slope currents, instability and meanders; eddies; tides, surges and coastal-trapped waves. Present and planned measurements to improve this assessment are discussed; also implications and prospects for modelling.

Introduction

Interest in the continental shelf edge has increased in recent years. For example, exchanges and the possibility of an active ocean-shelf boundary, with particular shelf-edge contributions to fluxes, are of topical interest for global fluxes, budgets and their response to climate change and human activities (e.g., Wollast, 1993). Physical processes underlie shelf-water characteristics and many such fluxes.

The need for improved process understanding is illustrated by contrasting satellite remote-sensed images west of Scotland. A sharp shelf-edge boundary to a coccolithophore bloom on 17 May 1980 (CZCS; Pingree and Mardell, 1981) suggests a strong bathymetric constraint, whereas the water mass boundary (to the Scottish Coastal Current) showing on 13 April 1981 (IR; Booth and Ellett, 1983) is on the shelf, suggesting freer exchange across the shelf edge. Moreover, the spatial and temporal measurement scales required for flux estimates remain unknown in general.

Currents varying on time-scales of days or longer tend to be constrained by geostrophy to flow along depth contours, inhibiting ocean-shelf exchange. Other factors may facilitate exchange:

- processes enhanced or special to the shelf edge (e.g., Huthnance, 1981)
- proximity to the equator (weaker geostrophic constraint)
- friction relaxes the geostrophic constraint, notably in Ekman layers
- shorter-scale excursions combined with non-conservative processes, for net <uC>.

Unfortunately, coherent estimates of <uC> checked by budget closure are rare.

This lack of naive estimates of flux suggests a more informed approach through process understanding, and model development and testing for representation of processes. Then extrapolation and integration over processes, space (context) and time can be carried out by extending the models.

Initial Assessment of Processes

The following have been considered as potentially influential processes in ocean-shelf exchange, water-mass structure and general circulation, according to their scales and context:

- coastal trapped waves
- along-slope currents
    - western boundary currents
    - relation to ocean circulation
        - boundary current separation
        - secondary circulation
    - instability, meanders, eddies
- Ekman transport and upwelling
    - jets, squirts and filaments
    - downwelling and cascading
- tides, storm surges, inertial currents
- fronts
- internal tides and waves
- surface waves
- capes and canyons
    - cross-contour flow
    - local upwelling
    - wave reflections

For this purpose, literature has been reviewed, and theory and previous measurements interpreted. More details are in Huthnance (1995).

Interim Conclusions by Process

Coastal trapped waves underlie and control phenomena important to ocean-margin circulation, exchange and mixing, rather than making an independent contribution. Their magnitude is generally determined by the forcing of a "primary" phenomenon. They propagate effects of forcing from one location to another along the shelf, and may make a distinctive contribution to the magnitude of circulation and exchange, via a near-resonant response or propagation to a shelf/slope sector of.different character (e.g., narrower). We still lack a complete description of super-inertial waves.

Along-slope currents may be driven with speeds O(0.1 m/s) by a variety of forcing mechanisms: fresh-water runoff: the oceanic density and associated pressure field; winds - either steady or unsteady with biased form drag; upwelling; non-linear waves, tides or eddies; geostrophic adjustment following mixing. Transfer and deposition of momentum by internal lee waves may redistribute the current. Different cross-slope distributions and ageostrophic cross-slope "secondary" circulation correspond to the different types of forcing, which still need to be resolved in many contexts. Along-slope continuity (distinguishing dynamics, transport, and water mass) remains an issue. The relation to oceanic circulation needs further clarification, with scope for investigation using simple ocean models and a cross-slope section (Fig. 1). Existing model solutions appear to be partial, e.g., Huthnance (1984) omits the effect of stratification on the sloping boundary layers; boundary solutions reviewed by Garrett *et al.* (1993) typically omit alongslope pressure gradients representing sustained forcing, alongshore flow divergence and time-dependence, any of which may assist cross-slope flow and matching to oceanic flow. *Western boundary currents* appear to be distinct as part of the ocean circulation, and show (relative to their greater strength of order 1 m/s) limited exchange with the shelf; *eddies* and streamers in Gulf Stream Warm Core Rings (for example) do show some exchange.

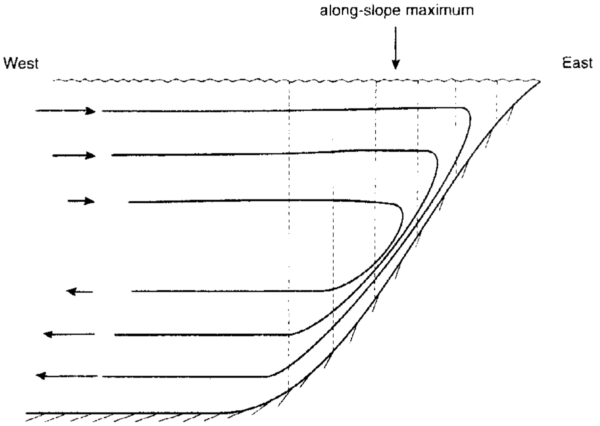

Figure 1. Schematic cross-slope section. Streamlines of cross-slope exchange (—) match the baroclinic shear (→) associated with the oceanic density field and form the Ekman transport under an along-slope current (velocity contours ---). However, solutions allowing for buoyancy forces in this section are the subject of continuing research.

Upwelling and *downwelling* juxtapose ocean and shelf waters in structures depending on the context and duration of forcing. Hence they enable mixing to change water masses and bring about ocean-shelf exchange, especially locally in jets and filaments. *Cascading* (e.g., Fig. 2) also tends to be local, the result of dense water (e.g., from winter cooling or salinated by evaporation or ice formation) finding a route off the shelf below the less dense adjacent slope water. Initially, cascading may be caused by instability of the flow in geostrophic balance with the cross-slope gradient of density, or it may be in the bottom Ekman layer under this flow; then any depression in the shelf edge is liable to facilitate and concentrate the process; hydraulic control may then operate. There is a need for measurements over long periods to improve statistics and estimates of the magnitude, space- and time-scales of these often intermittent and seasonal events.

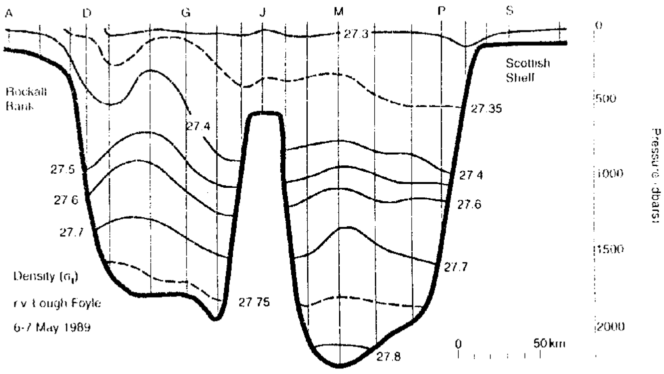

Figure 2. Evidence of late-winter cascading, 1989, off the eastern side of Rockall Bank near 57½°N, 13½°W (D.J. Ellett, personal communication).

Tidal and *wind-driven* currents are important in many shelf and slope seas, notably the north-west European shelf where they commonly exceed 0.5 m/s and are generally the largest contributor to turbulence, friction and mixing. Inertial currents may be particularly important to vertical mixing in the interior via their associated shear. Although transports are large (and long-period winds may drive substantial along-shelf displacements) the cross-slope flow is oscillatory, tending to limit exchange to the results of shear dispersion. Tides and wind-driven currents in homogeneous waters are quite well predicted, but measurements of mid-water turbulence would aid confident model predictions of inertial motions and associated mixing.

Fronts are associated with differential tidal mixing, fresher waters nearshore (Fig. 3) and well-developed upwelling. Cross-frontal transport and exchange depend critically on frontal instability and (e.g., frictional) relaxation of geostrophic constraints to allow cross-frontal flow. There remains scope for a general formulation predicting the occurrence of fronts, taking account of both buoyancy factors (surface heating, lateral freshwater input) and both surface stirring (wind, waves) and bottom stirring by tides.

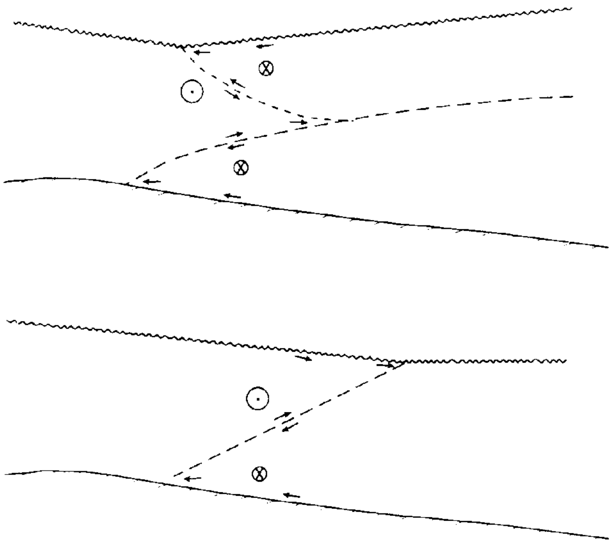

Figure 3. Schematic cross-front sections. (i) Tidal mixing fronts, between vertically mixed and summer-stratified seas, often have a strong density contrast across the lower interface. (ii) Fresher water on the shelf will tend to flow off-shelf above a shelf-break front. The sketch shows possible surface slopes (exaggerated) and gravitational cross-slope circulation (→, ←) associated with any (friction-induced) deficit in otherwise geostrophic along-slope flow (⊗ - into paper; ⊙ - out of paper, northern hemisphere).

Internal tides and *waves* are ubiquitous in the ocean, but of widely-varied magnitude according to location near the shelf edge, which is a principal generator of internal tides and consequent solitons contributing to the internal wave field. These motions are important to internal mixing, and to bottom currents and mixing where they are locally intense, notably in canyons. There remains a need for closely-spaced measurements of currents and temperature time-series, to test developing 3-D models of internal tides and waves.

Surface waves are often large enough to be important for near-surface mixing, but there is no special effect of the shelf edge in comparison with elsewhere in the ocean. Near-bed currents are small for typical shelf-edge depths, for all but the longest waves and shallowest shelves.

Along-shelf curvature of depth contours or changes of depth, associated with *capes* and *canyons*, may affect ocean-margin circulation, exchange and mixing processes in several ways: relaxation *via* small length scales of the constraint for geostrophic flow along depth contours; a "conduit" for the return of flow forced by winds (for example, Fig. 4) as the balance between wind stress and the pressure field varies according to depth; local intensification of upwelling or internal waves. In addition, the extra length of an irregular ocean-shelf boundary increases the scope for ocean-shelf exchange.

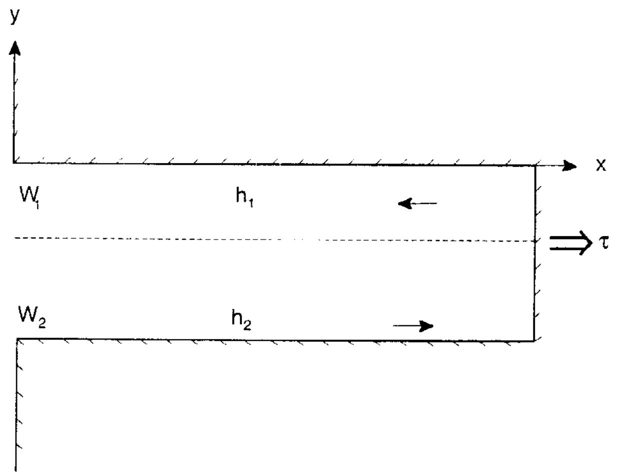

Figure 4. Deep embayment with wind stress τ inducing raised surface elevation at the head (right). The resulting exchange is *via* inflow in the shallower water "2" driven by the wind, and return flow in the deeper water "1" where the surface-slope-induced pressure gradient is more effective.

Comparison of Processes

This is synthesised in the following tables. These estimates are not uniformly applicable: they only apply where the process or phenomenon occurs; the magnitude scales according to the controlling variables via the formula given under "Scale." The numerical values derive from the given scale using "typical" values for the context, as given below (along with other notation).

Overall, many processes contribute O(1 m^2s^{-1}) exchange, albeit distributed in different ways through the water column (which will be significant according to the constituent transported). On this basis, internal tides (for example) are important only where exceptionally large, but upwelling should be important wherever it occurs. Larger exchanges potentially accompany boundary current divergence (although there is no evidence of values as large as tabulated), tides (but the return flow half a cycle later tends to reduce any longer-term transport), and canyons locally. Perhaps surprisingly, the Gulf Stream does not in practice seem to be the cause of larger exchanges than (for example) the relatively weak slope current around Scotland.

Table 1. Notation

Symbol	Meaning	Value	Unit
a	surface wave amplitude	1	m
A/hb	marginal sea area / entrance strait cross-section	10^5	—
C	constituent concentration		
c_p	specific heat	4.2	J/(g^{o}C)
C_D	quadratic bottom friction coefficient	0.003	—
d	deep ocean depth	4000	m
div	divergence in western boundary current	10^{-3}	km^{-1}
f	Coriolis parameter	10^{-4}	s^{-1}
g	gravitational acceleration	10	m s^{-2}
g'	reduced gravity: g × density change across thermocline / ρ	0.01	m s^{-2}
h	water depth (shelf and slope)	100	m
h_X	depth gradient across slope		
h_O	depth of principal oceanic circulation or thermocline	1000	m
$h_O/\Delta h$	ocean current depth / (ocean current depth - shelf-sea depth)	1	—
$h_O \lvert \rho^{-1}\nabla\rho \rvert$	steric slope	10^{-7}	—
h'	depth of seasonal thermocline	25	m
H	surface heat flux (winter cooling)	100	W m^{-2}
k	linear bottom friction coefficient	1	mm s^{-1}
k_I	linear friction coefficient below oceanic circulation	½	mm s^{-1}
L_T	topographic length scale h/h_X (over steep slope)	10	km
L_X/L_Y	ratio of zonal to meridional scales, oceanic gyre	5	—
N^2	squared Brunt-Väisälä frequency = $- g\rho^{-1}\partial\rho/\partial z$		
R_I	internal Rossby deformation radius = $(g'h')^{1/2}/f$ or Nh/f		
Sv	1 Sverdrup volume transport	10^6	m^{3}s^{-1}
t	duration of wind forcing	10^5	s
t_D	time constant for tidal shear dispersion	10^3	s
u	cross-slope velocity	0.1	m/s
$\mathbf{u}$	vector velocity		
v	along-slope velocity	0.1	m s^{-1}
V_W	western boundary current speed	1	m s^{-1}
w	wind speed	10	m s^{-1}
W_S	shelf width	100	km
α	thermal expansion coefficient	10^{-4}	(^{o}C)$^{-1}$
α'	frontal exchange coefficient	0.0055	—
β	northward gradient of Coriolis parameter	10^{-11}	s^{-1}m^{-1}
Δh_I	small random topographic irregularities	10	m
$2\Delta h/h_O$	where Δh is height of ridge with associated upwelling	1	—
∂_X	cross-stream gradient in western boundary current	0.01	km^{-1}
ζ	surface tide amplitude in shelf sea	1	m
	in marginal sea connected by narrow strait	0.1	m
$<\zeta>$	internal tide soliton amplitude	50	m
λ	combined length of internal solitons per tide	1	km
ρ	sea-water density	10^3	kg m^{-3}
σ	forcing frequency (e.g., tide, wind)	10^{-4}	s^{-1}
σ_W	surface-wave frequency	1	s^{-1}
τ	wind stress on sea surface (↔ wind speed ~ 10 m/s)	0.1	N m^{-2}
©	eddy circulation	10^5	m^{2}s^{-1}
<.>	ensemble average (usually effected as a space- or time-average)		

Table 2. Exchange

Process	Scale	e.g., m^2/s
slope current	kv/f	1
e.g., Atlantic inflow Malin-Lewis		(0.2 Sv / 300 km)
total Scottish slope		1
topographic irregularities	$v\ \Delta h_I$	1
eddy	$\copyright h_O(h_O/\Delta h)/f$	(1 Sv × 12 d)
warm-core ring streamer	?	(1 Sv)
aggregate (Middle Atlantic Bight)		0.3
impulsive wind	$\tau/\rho f$	1
upwelling - wind	$\tau/\rho f$	1
- div. W boundary current	$2h_O 2V_W \partial_X(V_W/\partial_X h_O)\mathrm{div}/f$	20
jets (narrow-shelf upwelling areas)	?	(2 Sv)
aggregate		2
front	$\alpha' h(g'h')^{1/2}$	0.3
e.g., along isopycnals, Middle Atlantic Bight		0.2
cascading(1)	$(0.6)^{-1}(g\alpha/\rho c_p)^{2/3}\, h(H^2/W_S)^{1/3}/f$	0.25
tides(2)	$\sigma\zeta W_S$	10
strait to marginal sea	$\sigma\zeta A$	(>1 Sv)
shear dispersion ($hu = \sigma\zeta W_S$)	$t_D uh\,\lvert \mathbf{u} \rvert/L_T$	0.1
internal tide solitons(3)	$<\zeta>\lambda/\mathrm{tide}$	1
waves' Stokes drift	$0.01w^2$	1
W boundary current and bend	$(h/h_O)^2(L_X/L_Y)\ \tau/\rho\beta$	(½ Sv)
slope current and bend θ	$v\theta kL_T/f$	(0.01 θ Sv)
cape eddy	hvL_T	(0.1 Sv)
canyon return flow(4)	$h\tau/\rho k$	10
ridge-associated upwelling	$(2\Delta h/h_O)\ \tau/\rho f$	1

Notes

Estimates in parentheses indicate exchange per "event" as distinct from a value per unit length of shelf.

(1) An along-shelf average is estimated, but cascading is liable to be localised down shelf-edge depressions.

(2) Tidal flows return only 6 hours later; the exchange may be only temporary.

(3) No value is typical; that given is large but may occur locally.

(4) Such values are localised to broad shelves such as the North Sea with an on-offshore canyon axis across the shelf width. However, canyons also facilitate many of the other processes and increase the length of shelf-edge boundary for exchange associated with slope currents and fronts.

Table 3. Circulation

Process	Scale	e.g., m s^{-1}
slope current forced by:		
JEBAR	$h_O^2 \lvert \rho^{-1}\nabla\rho \rvert g/8k$	0.1
steady wind	$\tau/\rho k$	0.1
unsteady wind(1)	$t\tau/\rho h$	0.1
biased form drag	$(\tau/2\pi\rho)\ \min(1/k,\ t/h)$	0.01
wave rectification(2)	$u^2 f/L_T\sigma^2$	0.01
eddy momentum	$uvh/L_T k$	0.1
western boundary current	$(L_X/L_Y)\tau/\rho k_I$	1
eddies, warm-core rings, jets	?	0.5
tides	$\zeta \max\{(g/h)^{1/2},\ \sigma W_S/h\}$	0.3
in strait to marginal sea	$\sigma\zeta A/hb$	>1

Notes

(1) In the presence of seasonal stratification, the effective depth h will be that of the upper layer down to the thermocline, ie. less, so that the upper-layer current (only) is greater.

(2) Internal motion, notably the internal tide, may reduce the effective length scale L_T to $(g'h')^{1/2}/\sigma$ so that the rectified flow is locally greater.

Overall, there are several agents of currents ~ 0.1 m/s, but in particular contexts western boundary currents, instabilities manifested as eddies, warm-core rings and jets, and tidal currents may be very much stronger.

Table 4. Energy potentially available for mixing

Process	Scale	W/m^2
surface waves	$1.5 \times 10^{-5}\ \rho g\sigma W a^2$	150
or	$5 \times 10^{-7}\ \rho w^3$	500
wind	τv	10
internal tides(1)	$\rho g'\langle\zeta^2\rangle\lambda/L_T$ per tide	50
internal waves	0.1×1 kW/m / L_T	10
bottom-reflected internal waves	fn(h_X, f/N) × 30 mW m^{-2} flux ↓	1
bottom friction	$\rho C_D v^3$	3
tidal(2) (currents 0.3 or 0.7 m/s)		100 or 1000
canyon-intensified internal waves(3)	$\langle\rho C_d u^3\rangle$	150

Notes

(1) No value is typical; that given is large but may occur locally.

(2) These dissipation estimates correspond respectively to an average and to locally greater values for the northwest European shelf.

(3) This estimate is local to the canyon floor where an empirical value 0.5 m s^{-1} is supposed for the intensified internal wave current.

These values highlight the importance of waves for surface mixing, of internal motions for mixing in the interior, and the highly variable importance of tidal currents and internal waves near the bottom, according to context.

Relation to Context

The estimates in these tables depend on the context (e.g., shelf width W_S, depth h, slope h_x, latitude through f, seasonality/N, winds through τ, waves, etc.). This dependence varies (e.g., some increase with W_S and others do not). Therefore the relative importance of different processes differs according to context. There is no one ranking of processes in order of importance. Paradoxically, the common estimate ~ 1 m^2s^{-1} for exchange may assist ranking in a particular context where there is a departure from typical values. Wind-driven exchanges vary as τ/f, for example, and are therefore larger in equatorial regions (for a given wind stress and appropriate direction) whilst tidal exchanges are even larger for a wider shelf.

Discussion

Flux estimated naively from measurements as <uC> is uncertain, owing to the need for a comprehensive yet intensive array in space and time. This derives from the geostrophic constraint on overall cross-slope flow, and hence a tendency for cross-slope flow to be relatively small in magnitude, with small time and space scales for structure and coherence. It is also necessary for the array to detect small correlations of u and C.

An approach through process understanding is therefore suggested. Present knowledge of processes' contributions to fluxes has been reviewed. On this basis, a classification of shelves might be attempted, firstly on local physical grounds according to shelf width, depth etc. An assessment of processes' global contribution should then take into account the length of shelf where a process is important.

Processes interact, and the ocean margin topography is complex. Therefore, it seems that numerical models must eventually be invoked to provide the sought-after synthesis over processes, time and space.

Measurements are essential to test models. The sequence of hypothesis (embodied in a model) suggesting experimental arrays, and measurements in turn causing model revision, is the essence of the scientific method. In the shelf-edge context, the choice of the model area and the need to initialise the model place a critical demand on measurements around the boundary of the experiment. Other competing demands on the experimental array are the need for duration to provide statistics of intermittent processes, versus detail to define their form; a compromise may be detailed measurements for a shorter duration to add value to measurements from a sparser long-term array.

Water-mass analysis provides a valuable complement to process studies in the form of an integrated (but uncontrolled) measure of cross-slope transport. Drogued buoys may provide an intermediate Lagrangian view, less integral but more controlled through the choice of deployment times and locations.

Measurements may be wanted in a variety of locations so that individual processes are well-developed to test their representation by models; yet there is a case for locations to be representative of significant lengths of ocean margin.

The developing interest in processes of shelf-ocean exchange, and the relationship between the nature of ageostrophy and the cross-slope structure of quasi-geostrophic flow, are reducing model resolution and the accompanying scale of required measurements to the internal deformation radius R_I, and in the vertical to an emphasis near the sloping sea-floor.

Model requirements on shelf-wide scales were discussed by Huthnance (1992). They include the representation of stratification, 3-D flow, friction, non-linear effects (notable for correct total friction and currents affecting slow waves) and forcing (wind, buoyancy) as appropriate, all with sufficient resolution in time and space. For finer-scale models, there are additional concerns. The model coordinates and advection scheme need to address simultaneously (i) the distribution of stratification and bathymetry such that the maximum of Nh_x over the sea bed can be described, (ii) advection over the sloping bed, and (iii) dynamical balance of the JEBAR term and of initialising data.

Although fine resolution is needed, shelf-edge models need to take account of phenomena in a large area; the extent of influence from 'upstream' may be 1000 km. This may be through open boundary conditions or embedding in a wider-area model. Either there are technical problems to be addressed in making the wider-area and nested models (two-way) interactive, or there is an intellectual challenge to finding 'off-line' open-boundary or matching conditions that are not interactive yet satisfy the needs of both the wider-area and fine shelf-edge models. One factor which may assist is that the distance 1000 km relates to the decay distance for a first mode coastal-trapped wave; if the large-area model has a good approximation to this (a relatively easy requirement on gross stratification and/or shelf/ocean depth ratio and shelf-slope widths) then the effect of poor boundary conditions in the fine model may relate only to higher modes and penetrate a much shorter distance before decay.

Hence there remains full scope for application of the scientific method through models and experiments - the latter at sea, in the laboratory and with simpler models. The emphasis is on fine scales R_I and near the sea bed, on the model grid in relation to stratification, bathymetry and advection, and on accounting for external influences in both experiment and model. In view of the prospective application of models, we have not attempted to be fully quantitative in estimating circulation, exchange transports and mixing rates. Rather, the aim has been to provide a basis for deciding what may be the important features and physics to include in a model of a chosen region, and the processes to be resolved in measurements to test models.

Table 5. Previous and planned studies

Previous experiment	Context contrast	Conclusions
Scotian Shelf	shelf-edge front strong T, S variations (cold air outbreaks)	long-period fluctuating transports
SEEP-I		
SEEP-II	no slope current eddies from Gulf Stream	stratification helps exchange
Southern Atlantic Bight	shallow shelf Gulf Stream alongside	dominance of GS changes associated upwelling
CODE (N California) Coastal Transition Zone Program	narrow shelf strong wind-stress curl strong summer upwelling jets, filaments weak tides	large exchange (?) via upwelling & filaments affects production features tied to capes and ridges
Concurrently	Characteristics	
SES (Hebrides, 1995-6)	slope current strong wind forcing	separate coastal current some upwelling, cascading
OMEX (Celtic Sea, 1993-6)	bends and canyon weak slope current	very wide shelf strong tides "upstream"
MORENA (Portugal, 1993-6)	narrow shelf	summer upwelling, etc.

OMEX (Ocean Margin Exchange) involves more than 40 European partners spanning interests in physics, chemistry, biology, sediments and air-sea exchange. It includes the review of processes oulined here, and the following moorings and other deployments:

- current meter moorings from June or December 1993; six over the southern Portugal slope and offshelf, four over the Goban Spur, and (from April 1994) three north-west of Ireland in 660 m water depth;
- eleven drogued buoys over the slope off Portugal, deployed in December 1993, and possibly some more to be deployed over the Goban Spur;
- CTD sections contributing to the EC *Shelf Edge Fisheries and Oceanography Study*, which is altogether collating 15-20 repeated cross-slope sections off Western Europe.

OMEX also comprises remote sensing, and several modelling studies: internal waves, waves over the shelf and slope, ocean circulation and the eastern boundary, 3-D prognostic hydrodynamic modelling of the OMEX study areas. There are also many studies in the other disciplines.

SES (Shelf Edge Study, west of Scotland and part of the UK Land-Ocean Interaction Study) has the following measurement components:

- initial extensive survey (March 1995) of bathymetry and the sea bed along the slope (side-scan sonar, coring)
- six seasonal cruises (~ 3-monthly starting May 1995) with intensive surveys (ADCP, SeaSoar, CTD) and sampling (for chlorophyll, nutrients, tracers)
- mooring array (some maintained for 18 months): one main cross-slope section near 56.4°N and a reduced array ~ 25 km along-slope to the north
- tracking of instrumented drogued buoys
- satellite remote sensing.

SES is also funding studies of internal tides and waves; the along-slope current and its continuity; interpretation of the drogued buoy tracks for eddies, dispersion and exchange; ocean-shelf exchange by tracers/water mass; laboratory models (internal and long waves); 3-D prognostic numerical models; several studies in other disciplines.