# OCEAN SCALE AND REGIONAL COMPARISON - ESTUDIOS OCEANICOS Y COMPARACION REGIONAL

## PHYSICS AND FISH POPULATIONS: SHELF SEA FRNONTS AND FISHERIES

by

J.R. Hunter[1] and Gary D. Sharp[2]

[1]Southwest Fisheries Center La Jolla Laboratory
National Marine Fisheries service
NOAA, P.O. Box 271
La Jolla, CA 92038
USA

[2]Fishery Resources and Environment Division
Fisheries Department
FAO, Vai delle Terme di Caracalla
00100 Rome, Italy

Resumen

Entre los problemas de proyectar la producción de la pesca están la gran cantidad de variables complejas, dentro de las cuales la producción primaria y los procesos físicos que promueven esta producción tienen gran importancia. Se revisa una vez más la importancia de las escales de tiempo y espacio en relación a varios procesos biológicos de importancia relacionados con la pesca, y se describe una clase especial de fenómeno físico y sus características.

Los frentes marinos en la plataforma derivan de numerosos procesos: frentes en la interrupción de la plataforma; frentes costeros; corrientes sobre la plataforma impulsados par el viento; frentes causados por las mareas. Estos se describen en suficiente detalle como para que sus mecanismos puedan ser comparados, y se describen las características de los frentes marinos de la plataforma. Estos son procesos determinados por las estaciones y la geografía.

Los requerimientos para que se forme un frente son de dos tipos:

a) Debe haber suficiente energía (del viento a las mareas) para formar un área de mezcla, con una región adyacente donde el grado de mezcla, con una región adyacente donde el grado mezcla es menor y puedo ocurrir estratificación.

b) para que ocurra la estratificación debe haber una fuerte presión o empuje hacia arriba del fluido ya sea por el incremento de la densidad capas superiores, por ejemplo lluvia o pérdida de calor.

Si se tiene información sobre la observación de energía y los procesos de estratificación es posible hacer una serie de prediciones sobre dónde se pueden generar los frentes marinos en la plataforma. Las Principales áreas de plataforma continental de los océanos del mundo se han ordenado para mostrar las regiones potenciales para la formación de frentes inducidos por mareas. Estos parecerían ser útiles para relacionar con áreas de producción de peces pelagícos-neríticos, tal como fuera sugerido por Illes y Sinclair (1982) para *Clupea harengus* frente a la costa

este de Canadá, y posiblemente merezca una mayor atención en relación en relación al potencial pesquero y sus variaciones.

## INTRODUCTION

Since the advent of concern about the long-term productivity of the seas in the face of man's predation and perturbations, as reviewed in Thomasson (ed. 1981), there have been numerous general attempts to quantify system potentials, either via attempted simplification utilizing trophic concepts (Hardy 1924, Steele 1974, Cushing 1971), or through study of life table statistics arising from samples taken from fisheries and research ventures on many species (Beverton and Holt, 1957, Ricker 1958, Andersen and Ursin 1977). Numerous techniques have been applied toward obtaining estimates of the amounts, distributions and status of fishery resources. As yet no technique has been particularly successful at projecting fishery production, primarily due to the species and physical oceanographic variations arising from complex climatic and biophysical interactions.

As various management regimes have failed to stabilize fish populations, and there fore production for one reason or another (e.g. Saetersdal 1980), the recent generation of stock assessment specialists is once again opening their ranks and fora to discussions of what variables beyond fishery statistics need to be considered in order to resolve or interpret the variations in population production.

There have been few revolutionary concepts introduced since the early insights of Johan Hjort (1914); Baronov (1918), Michael Graham (1935); or Peterson (1894). The variety of permutations and analytical approaches arising from these original observations, assertions, and interpretations are reasonably well documented in the recent surge of “how to” stock assessment manuals (Laurec and Le Guen 1981, Beyer and Sparre 1983, Pauly, M S). The latter reference even provides examples and programmes on magnetic cards for use with small desk top programmable calculators. These manuals cover virtually all conventional stock assessment techniques. This makes available the possibility to do the rather trivial mathematical operations in single species stock assessment to anyone capable of acquiring data and entering them into a keyboard, and leaves far more time to think about the more difficult problems of interpreting the results, and deciding what new or other parameters need to be incorporated in order to rationalize fishery management.

The more complex models is incorporating more than one species are not so readily available. Laevastu and Larkins (1981) have provided an introduction to the ecosystem model which evolved at the Northwest and Alaska Fisheries Center in Seattle, Washington. This model comprises many thousands of computer statements and as such cannot be rightly condensed so as to operate on a desk calculator. Laevastu has however created a “teaching tool” version of the biological interactions segments of the ecosystem model which is available upon request.

Perhaps more important is the general trend in development of the conventional wisdoms to include, once again, ambient environmental (biotic and abiotic) parameters into stock assessment techniques. This has come about through the increasing awareness of the importance of early life history survival requirements, and causes of mortality associated with predation, starvation, and environmental perturbation, i.e. pollution or habitat destruction.

No attempt will be made here to review the so–called stock–recruitment problem, as this has been quite thoroughly done by Ricker (1954); Sharp and others in IOC Workshop Report No. 28 for oviparous fishes; Garcia (in press) for penaeid shrimp; and Hennemuth et al., (1981) for a variety of species. The further information needed in relation to the S/R problem is outlined in Bakun et al., (1982), and Sharp (1981a) and will be one subject of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Stocks in Costa Rica from 18 to 29 April 1983.

What is becoming increasingly apparent is the relevance of smaller scale ocean processes in setting the limiting survival factors for each component of potential breeders in marine populations. This follows directly from the insights of the early fishery scientists mentioned above, but has grown to be of major research concern only in the recent decades. This is not to say that there has not been substantial continuing effort since G.M. Dannevig released the first few hundred thousand Gadus morhua larvae hatched at the F1φdevigen Sea Fish Hatchery in 1886. But even at that time there were heated arguments over what caused the natural variations in cod populations. The eventual instigator of the "critical period" concept, Johan Hjort, was one of the leading critics at the onset of this project. Now, one hundred years later, Norwegian scientists are re–emphasizing the field of enhancement of natural populations through laboratory rearing, sea ranching and release programmes, with scaled feasibility studies as a basis for each stage in development (Sharp 1981c).

The major advocates of increasingly sophisticated studies of larval fish requirements have been Rosenthal (1970), Jones (1974), Lasker (1975, 1978), Laurence and Beyer (1981), Houde (1974, 1975, 1978 and 1980) and recently IMARPE staff at Callao, Peru. Theilacker and Dorsey (1981) reviewed relevant research results and have made several observations and recommendations regarding required standardization of techniques and reporting of results of studies of larval fish feeding, survival and growth, if such studies are ever to be compared in a meaningful fashion.

Cannibalism and predation on larval and juvenile fishes is recognized as the major mortality source resulting from other than larval fish feeding requirements (MacCall 1981; Smith and Lasker 1978; Andersen and Ursin 1977; Alvariño 1980).

Other parameters which need more attention are those for physical processes which have been identified as important to the early life history stages and adults as well, namely gyres, frontal systems, horizontal microstructure and eddy systems in general (Bakun and Parrish 1981, Parrish et al., 1981, Owen 1981, Grainger 1980; and Illes and Sinclair 1982). These authors have discussed various neritic fish resources in respect to the physical transport phenomena associated with near shore, coastal fish populations.

Reid et al., (1978) and Voronina (1978) have described oceanic zoogeographic provinces in relation to ocean-scale circulation. The reviews of the hydrodynamics of semi– enclosed seas such as the Gulf of Mexico, the Mediterranean Sea and the Baltic (Nihoul, ed. 1982) indicate strong eddy and gyral phenomena dominate these areas, certainly having significant biological consequences.

What is needed is a catalogue, so to speak, of processes, habitat features and their geographic and temp oral distributions so that it might be possible to better understand the phenomena which promote or delimit neritic and oceanic fishery resource production potentials in their realistic, dynamic form.

Illes and Sinclair (1982) have stimulated this particular publication by pointing out the dependence of herring (Clupea harengus) populations, i.e., breeding components, upon gyral strengths, distributions, and persistence. What is implied is that the discontinuity of occurrence of a species on the short or long-term, indicates that there are specific, physically mediated requirements which occur within the same pattern of the species distribution. These are often physical processes which promote essential productivity of food, and, in the case of Atlantic herrings, simultaneously maintain larval coherence within the optimal survival conditions. The more mobile juvenile and adult stages are less "controlled" by the local physical processes, but respond in the case of drastic changes.

Similar phenomena and other transport processes are described by Parrish et al., (1981) which they use to explain the reproductive behaviour, species success and general zoogeography of the California Current. Sharp (1981b) reviewed numerous interactive phenomena scaled in relation to species mobility ,larval requirements, food production and homing versus opportunistic species which can account for the vast behavioural array and species diversity observed in most regions.

The concept of variable carrying capacities for either early life history stages or adults needs careful consideration. The implications for portrayals of species variations, monitoring and forecasting variations, or hind casting variations in variously behaving species are determined hierarchically by the magnitudes and variations in the important limiting physical processes, and whether these affect primarily early life history stages, or later stages. The near total dependence of early life history stages upon "local" conditions, in contrast to the numerous behavioural options available to more mobile stages, makes this an important consideration.

Now that the importance of early life history effects is better documented and various criteria for survival are being defined, it would be appropriate to step back from the fine scale processes, and look over the global and system scale properties of neritic zones as a first stage in focussing on the system dynamics relevant to fishery resources and their relative fragility.

Upwelling areas have been well documented as the sources of particularly high coastal nutrient and subsequent biological production (recent review in Richards 1981, Cushing 1972, Glantz and Thompson 1981, and Szekielda et al., 1977). Recent efforts to identify other sources of productivity (Gieske et al., 1979, Owen 1981, Pingree et al., 1978 and Gregg 1980) point to the thermocline - picnocline and their vertical counterparts, recognized as fronts of various types as widely occurring features harbouring production in various forms and scales, from meters to kilometres in horizontal dimensions and centimetres to meters in vertical dimensions. Mann (1982) reviews production and energy transfer in coastal systems. Fasham (1978) reviewed the relative inadequacies of conventionally obtained plankton data in resolving these relevant scales of occurrence of ocean productivity. It appears that we are entering another age of discovery in this field , particularly as one takes into account the spontaneity of primary production processes and the responses of fish populations. The relative persistence, dynamics and interactions of fish populations and their invertebrate counterparts, are tied in various fashions to the same physical processes as promote, isolate ,and disperse the plankton populations supporting the food webs. As the fish resources usually start out in the plankton, graduating in size and relative independence with time , these physical features which promote production and /or aggregation need to be better defined, monitored and evaluated if we are ever to understand the true resource potential, their dynamics and their distributions. Sverdup was saying this 30 years ago (1952, 1955), Chapman 10 years ago (1972) and Bakun , Beyer, Pauly, Pope and Sharp said it again last year (1982) with perhaps a few more direct links between fish, plankton and physical processes from which to begin.

Shepherd, Pope and Cousens (ICES 1982) have summed up rather well the distinctions between various environmental processes which are likely to directly affect fish resources, from 1) direct physiological effects due to temperature, oxygen, salinity, pressure, etc; 2) disease; 3) feeding effects such as food abundance, food quality, time–space variations, localization of concentrations and competition; and 4) predation, the result of one individual being food for another, hence starting the cycle in 3) again. That these authors were also able to convince themselves that there are indeed statistically verifiable links between young fish survival and climate is satisfying, but not news.

In regard to production of food and sustenance offish populations, one source of primary production and aggregation phenomena which has only recently been given due consideration is the phenomenon of shelf sea fronts (Anon., 1981). In this collection of studies Holligan (1981) characterizes the primary and related secondary production emanating from northwest European continental shelf fronts. He also classifies variously generated fronts, describing shelf-break fronts, coastal fronts, and the relatively important tidal fronts which have been observed in varying detail. Such observations have been made for the Ushant frontal system which extends around the coast of Brittany into western English Channel (Pingree et al., 1975, 1977, 1979, Grall et al., 1980), the Celtic Sea front between Ireland and Wales Savidge 1976; Savidge and Foster 1978, fronts in the Irish Sea (Savidge 1976;Foster et al., 1976; Beardall et al., 1978), the Isly front between northern

Ireland and Scotland Pingree et al., 1978; Simpson et al., 1979) and the fronts around the Orkney and Shetland Isles (Pingree et al., Dooley 1978, and southern North Sea (Harding et al., 1978).

Allen and Smith (1981) describe wind driven shelf currents off Oregon, northwest Africa and Peru, each being uniquely controlled, some more by wind, others more by longshore currents and topography. The common denominator of these currents and shelf frontal systems is that they both promote eddy formations (Simpson 1981; James 1981), which through initial nutrient injection can set primary production going and zoo-plankters and fish aggregating into these systems may provide sufficient additional and recycled nutrients to sustain this production over a relatively longer period. The vortices or eddies may provide perfect larval fish development conditions (Illes and Sinclair 1982) and larger eddies, as for example off Southern California (Owen 1980, 1981, 1982) may provide adequate nutritional aggregation for sustaining fish reproduction, coherence of reproduction products through subsequent developmental processes, and even maintain the young fishes within a specific geographic situation which might not sustain some pelagic populations otherwise (Parrish, Nelson and Bakun 1981).

In recognition of the relevance of shelf fronts to fish aggregation and reproduction, particularly tidally generated shelf fronts, the following general description of what they are all about is offered.

## SHELF SEA FRONTS

Tidal shelf sea fronts are regions of strong horizontal variation in density, separating vertically stably stratified and well mixed regimes. Vertical density stratification is generated when there is some buoyant input to the sea, such as through surface heating, or runoff of fresh water (the majority of known tidal fronts are associated with the former mechanism). When water is stably stratified, it has lower potential energy than the same system would have after complete vertical mixing (since its centre of gravity is lower). Hence vertical mixing of the water column requires the input of energy. This comes primarily from tidal stirring and from the surface wind stress (on the North West European shelf, the former is more important (Simpson, Allen and Morris, 1978), while in areas such as the Arabian Gulf tides and wind may exert comparable influences (Hunter, 1982).

The balance between the input of buoyancy (and consequent lowering of the potential energy of the water column), and the addition of energy through mixing determines whether stable stratification will occur. If buoyancy input is high we may get stratification, while if mixing is high we may not. In regions where the buoyancy flux and/or the tidal mixing changes markedly in the horizontal, we may find a change from one condition to the other, generally associated with a strong horizontal gradient (a “front”).

The energy argument for the occurrence of tidal fronts was originally given by Simpson and Hunter (1974) who concluded that the presence of such fronts should be predictable from the parameter

$$\frac{h}{u^3}$$

where h is the water depth,

and u is the tidal stream velocity

(the reciprocal of this parameter is proportional to the tidal dissipation per unit volume of sea water).

Since the tidal velocity occurs as a cubic power law in the above expression, this parameter covers a wide range in the shelf areas of the world - on the North West European shelf it varies over three orders of magnitude (Simpson, Hughes and Morris, 1977), which means that there is ample scope for the formation of tidal fronts in this region.

Shelf seafronts have generally been associated with buoyancy (i.e., less dense water) added at the surface (e.g., by heating, or freshwater inflow). However, vertical stratification can also be caused by the addition of negative buoyance by processes such as surface evaporation. This case is some what different from those considered already, in that surface addition of negative buoyancy (dense water) yields an unstable system denser water overlying light water) which will overturn, generating some mixing as it does so. However, the resultant water, even if vertically mixed, will still be denser than the water in an adjacent region where the evaporation may be less, and this horizontal density gradient can give rise to vertically sheared flows, the denser water passing underneath the adjacent lighter water. This phenomenon is common in tropical seas where evaporation is often a dominant buoyancy flux - dense water is formed in shallow areas where evaporation is highest (both due to the lower relative humidity near the coast, and (in summer) to the higher sea temperatures near the coast) and where a given rate of evaporation yields a greater density change, leading to an "inverted estuarine" circulation (seaward at the bottom, shoreward at the surface). A good example is the Arabian Gulf. It is quite feasible that horizontal fronts could be generated in such areas by lateral variation of tidal and wind mixing processes.

The physical and biological implications of sea fronts were recently reviewed at a conference organized by the Royal Society (Anon., 1981).

## THEORY

A simplified derivation of the "$h/u^3$" law will be given here. More detailed accounts have been given by Simpson and Hunter, 1974; Fearnhead, 1975; Simpson, Allen and Morris, 1978; and Simpson and Bowers, 1981.

Buoyancy may be described as a density anomaly in the sea water, and its "concentration" may be defined quantitatively by

$$-g(\rho - \rho_0)$$

where g is the acceleration due to gravity,

$\rho$ is the sea water density,

and $\rho_0$ is a constant reference density

(note that $\rho - \rho_0 >> \rho_0$).

As this factor depends only on density ,it is an intrinsic property of the sea water, and as such is conserved in any system when due consideration is made of any sources and sinks of buoyancy. Buoyancy may be modified by the addition or removal of heat or salt, and it may be transported around the sea like any other "contaminant" (i.e., by deterministic flows ("advection") and by turbulence ("dif– fusion")). For small additions of heat or salt, the buoyancy change will be proportional to the quantities of heat or salt involved (in the case of evaporation, the removal of fresh water may be interpreted as an addition of salt, if desired).

The addition of buoyancy decreases the potential energy of the water column. It can be shown that the rate of decrease in potential energy ,if all the buoyancy is concentrated at the surface is given by

$$\frac{Bh}{2} \text{ per unit horizontal area of the sea} \quad (2)$$

where B is the rate of addition of buoyancy per unit horizontal area of the sea,

and h is the depth of the water column.

(We here choose our zero of potential energy as that of the water column after complete mixing to a uniform density distribution. This formulation neglects any work done by atmospheric pressure if the volume of the water column changes during the mixing process. This assumption is reasonable for small density changes, over which it may be assumed that the density varies proportionally with temperature and salinity).

If no mixing were applied to the water column the potential energy would decrease continually with a larger and larger density anomaly at the surface. However, the presence of mixing increases the potential energy of the water column and may prevent the formation of stratification. Mixing in the sea is accomplished almost exclusively by turbulence, which is generated by the presence of large-scale shearing flows, predominantly associated with tidal and wind-driven currents. Turbulence removes energy from these currents, and most of this energy finally appears as heat. However a small proportion (of order 1 percent) may be made available for removing any stable stratification, thereby increasing the potential energy of the system. The rate of abstraction of energy from a sheared flow is proportional to the shear stress in the fluid, multiplied by the velocity shear. If we consider the whole water column, then turbulent energy is introduced at the boundaries due to slip in layers associated with these boundaries (the "boundary layers") - the upper one due to the surface wind stress, and the lower one due to the tidal current . Each boundary layer introduces turbulent energy equivalent to the boundary stress multiplied by the "slip velocity" across the layer. Boundary stresses in the sea are generally proportional to the square of the slip velocity

$$\tau = \rho C_D v^2 \qquad (3)$$

where $\tau$ is the stress,

$\rho$ is the water density,

$C_D$ is a dimensionless drag coefficient,

and $v$ is the slip velocity.

The rate of generation of turbulent energy is hence related to the cube of the slip velocity

Rate of generation = $\tau$ v per unit horizontal area

$=\rho C_D v^3$ per unit horizontal area

For tidal currents, "$V$" is approximately the tidal stream velocity, while for wind generated turbulence, it is the surface wind drift (roughly 3 percent of the wind speed).

Simpson and Hunter, 1974, assumed that the quantity of energy available for mixing was related to (4) by a constant of proportionality, $\xi$

Rate of supply of energy for mixing $=\xi\rho C_D v^3$ (5)

The onset of stratification of a water column should hence be determined by a balance of (2) and (5) - i.e., there is just enough buoyancy input to overcome the possible gain in potential energy due to mixing

$$\frac{Bh}{2} = \xi \rho \, c_D \upsilon^3$$

or

$$\frac{h}{\upsilon^3} = \frac{2 \xi \rho c_D}{B} \quad (6)$$

If, over a given sea area, the right hand side of (6) is constant, then the region where stratification can just occur (i.e. a "front") should be associated with a constant value of "$h/v^3$". This has been shown to be the case for tidal fronts on the North West European shelf (Simpson and hunter, 1974; Simpson, Hughes and Morris, 1977; Simpson, Allen and Morris, 1978; Pingree and Griffiths, 1978), in the Gulf of St. Lawrence (Pingree and Griffiths, 1980), in the Bering Sea (Schumacher, Kinder, Pashinski and Charnell, 1979), in the Bay of Fundy and Gulf of Maine (Garrett, Keeley and Greenberg, 1978), and in the Cook Strait (Bowmna, Kibblewhite and Ash, 1980).

As the parameter "$h/v^3$" and vary widely, the logarithm of this quantity is generally used to derive a STRATIFICATION PARAMETER, several of which have been defined

(a) $S_s = LOG_{10}(h/u_s^3)$ (7)

where $u_s$ is the surface tidal current amplitude at Springs, and h and $u_s$ are in SI units. (Simpson and Hunter, 1974, and other references associated with Simpson)

(b) $S_p = LOG_{10} [h/C_d < |ut|^3 >)]$ (8)

where $< ut^3 >$ is the time average of the depth meaned tidal velocity cubed, and h and ut are in GCS units.
(Pingree and Griffiths, 1978, 1980)

(c) $S_{G1} = LOG_{10} [h/(\rho C_D < |ut|^3 >)]$ (9)

where h, ρ and ut are in SI units.

($S_{G2} = LOG_{10} (h/v^3)$ (10)

where v is the depth-meaned velocity amplitude for mean tides, and h and v are in SI units.
(9) and (10) due to Garrett, Keeley and Greenberg, 1978).

(d) $S_H = LOG_{10} (< |ut|^3 >/h)$ (11)

where h and ut are SI units.
(Hunter, 1982)

At a given place, these are related approximately by

$$S_s = S_p + 0.57 = SG_1 = SG_2 - 0.45 = -(S_H + 0.82) \quad (12)$$

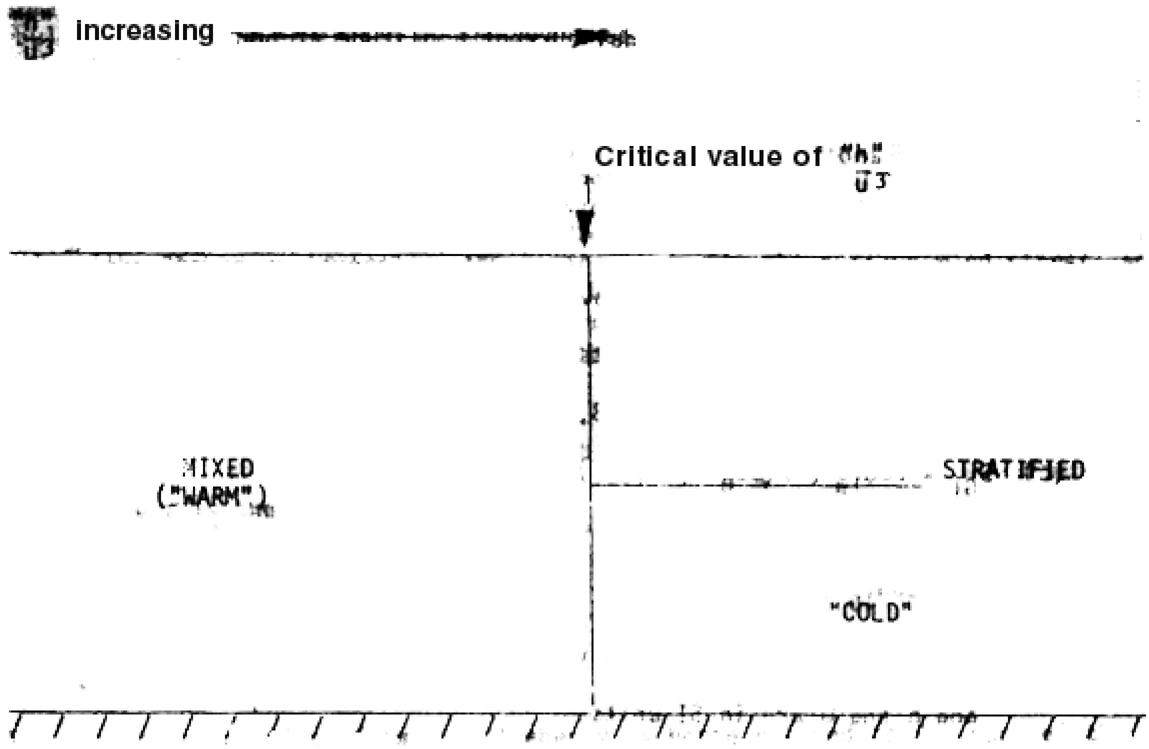
For the waters of the North West European shelf, the position of a front is predictable approximately from

$$S_s = 2 \quad (13)$$

(Simpson, Hughes and Morris, 1977; Pingree and Griffiths, 1978)

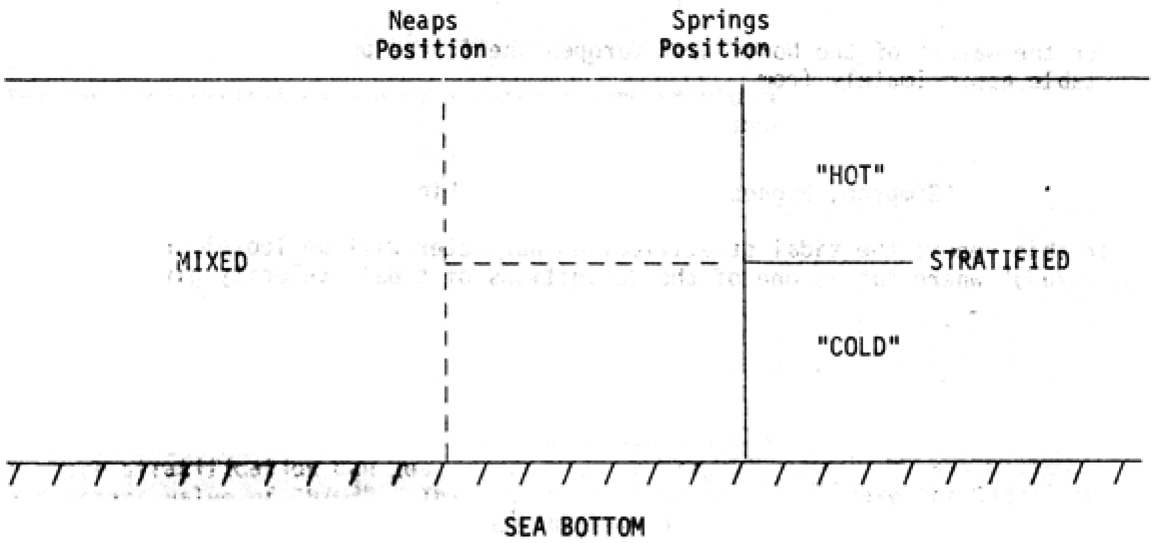
In this report the tidal stratification parameter will be loosely referred to as "$LOG_{10}(h/u^3)$" where "u" is one of the definitions of tidal velocity given above.

A schematic representation of a front is given below




This simple picture of the position of a front fixed in space may be modified by a number of factors.

(a) The mixing rate varies over the Spring-Neaps cycle (being a maximum at Springs), so we would expect the position of a front to oscillate over this period, being displaced towards the mixed water at Neaps and towards the stratified water at Springs



The expected movement of the front may be calculated from the variation of tidal velocity from Neaps to Springs(and any change in depth associated with the local bathymetry). However, observations have shown that the actual movement that can be attributed to this cause is considerably less than this (Simpson and Bowers, 1979) (the observed Springs/Neaps adjustment is typically 4 km). This discrepancy has apparently been resolved by modifying the simple model, and allowing the efficiency factor for mixing "$\xi$", to vary with stratification (Simpson and Bowers, 1981) - it is known that vertical stratification inhibits mixing, and so it seems reasonable that "$\xi$" should decrease with stratification. Simpson and Bowers have shown that such a "variable efficiency" time-dependent model predicts considerably less frontal movement over the Neaps-Springs cycle. This modification to the model also leads to better agreement on frontal position over the summer season- the "constant efficiency" model predicts a marked advance of the front( towards the mixed water) in Spring, and a similar retreat in Autumn, not in accordance with observations, which show an almost constant frontal position from early June to late August (as predicted by the "variable efficiency" model). A further advantage of the variable efficiency model is that it predicts strong horizontal gradients in the degree of vertical stratification (i.e. a sharp front ) also in accord with observations.

(b) Frontal positions may also be modified by any water velocity normal to the front. There are several manifestations of this

(i) Tidal velocities, which advect the front back and forth. This is a major cause of the observed scatter of the positions of a given front in European waters - for a straight front, the displacement is simply given by the component of the tidal excursion normal to the line of the front.

(ii) Eddy-like features on the front. These have been observed in infra-red satellite images, and may draw their energy from the potential energy of the stratified fluid (baroclinic instability) or from the kinetic energy of the fluid (e.g., from tidal currents). These eddies may have scales of order tens of kilometres, but their dynamics are not well understood.

(iii) Steady flows. These may systematically distort the line of a front away from the position predicted by "$h/u^3$" contours, as is probably the case with the front off Islay, to the North of the Irish Sea. In the case of an island, around which a front would be predictable from "$h/u^3$" values, a wake of mixed water may be formed in the downstream direction (e.g., the Scilly Isles) (See Simpson, 1981, for these examples).

Although the detailed position of a front may be changed from that predictable from a simple "$h/u^3$" criterion, by the above effects, this basic rule still serves as a good indicator of the areas in which fronts would be expected to occur.

The requirements for the occurrence of a front are mainly twofold

(a) There must be sufficient tidal (or wind) energy to form a mixed region, and conversely there must be adjacent regions where mixing is less and stratification can occur. As a rule of thumb, frontal structures seem to be found in areas of the world known for their high dissipation of tidal energy (e.g. the North West European Shelf, the Bay of Fundy and the Cook Strait).

(b) A condition for the formation of stratification is the supply of buoyancy to the fluid. This buoyancy is equivalent to a certain amount of negative potential energy that must be removed by supplying positive energy if vertical homogeneity is to occur. The relationship between buoyancy and potential energy is however dependent on where the buoyancy is put in - for instance, the potential energy of a column of water may be made more negative by the addition of positive buoyancy (light water) at the surface (the case we have considered up until now) or by the addition of negative buoyancy (heavy water) at the bottom. It is important to understand that the mixing processes described do not remove buoyancy - they simply increase the potential energy in a positive sense. If buoyancy (equivalent, for example, to heat or fresh water) is allowed to accumulate, then eventually some feedback process will" switch off" the buoyancy supply - for the case of heat, the sea will continually warm until surface losses balance the solar heating (as is the case for the daily- averaged conditions of a tropical lake). In such cases, any mixing processes will eventually mix the water vertically, removing any frontal structures originally present. There would appear to be two ways of getting round this problem

(i) If the buoyancy supply is periodic (e.g., seasonal), then during the buoyancy supply phase buoyancy can be stored in the water column, to be removed later during the buoyancy removal phase. This of course is what happens during the summer/winter cycle in non-tropical areas, and is the case for most of the examples of tidal fronts found in the literature.

(ii) The buoyancy may be added at one point in the water column, and removed at another, thereby avoiding any accumulation of buoyancy. For instance, positive buoyancy could be added at the surface and removed at the bottom, thereby decreasing the potential energy of the water column through the formation of a light layer at the surface and a heavy layer at the bottom. This case could be applied to tropical areas and only a simple modification (i.e., a positive and negative buoyancy supply) need be made to the basic model. Frontal positions would still be predictable from "$h/u^3$" contours, so long as the buoyancy sources were reasonably constant horizontally. The mechanism for the removal of buoyancy from the bottom could be by lateral advection of mixing. A common example of this is an estuary, where positive buoyancy (fresh water) is added at the surface at the landward end and negative buoyancy (salty water) is added at the bottom at the seaward end. On average, no buoyancy accumulates in the estuary, and the negative potential energy input is balanced by tidal and wind mixing. In this example, the flows necessary to maintain the correct buoyancy balance are driven by the horizontal density gradients that arise from the buoyancy inputs - the system adjusts itself to yield a density structure that is roughly constant in time. In regions of an estuary where the mixing levels change in the horizontal, fronts may be formed. The above argument suggests that tropical areas, where the rate of heating does not vary much over the year and where the buoyancy input may be through heating, evaporation or the supply of fresh water, should not be discounted as regions for the possible formation of tidal fronts.

## TIDAL MIXING IN SHELF SEAS

For a given rate of buoyancy input, the position of a front should be predictable from a fixed value of "$h/u_3$". If we consider the value for the North West European shelf, for stratification induced by solar heating, from equation (13) $h/u_3^2$=100

$$\frac{h}{u_s^3} = 100 \qquad (14)$$

Hence for a typical depth of water over a shelf of 100 metres, the frontal position should coincide with the 1 metre per second surface spring tidal velocity amplitude contour. As noted in section (2), this represents an area of high tidal dissipation, by global standards.

The tidal dissipation of shelf seas of the world was investigated by Miller (1966). He divided the shelf into 50 regions, and from computations of both the tidal energy crossing the boundaries with the ocean, and of the frictional dissipation at the sea bed, he obtained values of total dissipation for each region. These areas are shown in Figure 1 (from Miller's map), and unfortunately they are of very different sizes, and so do not give a good indication of the energy density available for mixing the water column.

Consider a shelf of length "L" (alongshore), width "W" (offshore) and depth "h". Then from equation (4) the total dissipation of tidal energy over that shelf is given by

$$E = WL\rho C_D <|ut|^3> \tag{15}$$

where $<|ut|^3 >$ is the time average of the tidal velocity

(this may be a depth-meaned value, or a "bottom" value, so long as the drag coefficient "$C_D$" is chosen appropriately.)

and ρ and $C_D$ are as defined for equation (3).

"E" is the parameter estimated by Miller, and it is related to "$h/<|u|^3$"

by

$$\frac{h}{<|ut|^3>} = \frac{hWL\rho C_D}{E} \tag{16}$$

Now, "ρ" and "$C_D$" are approximately constant, and so we need to divide Miller's dissipation values ("E") by the value of the shelf water " hWL ") to estimate the variation in "$h/u_3$". This would be a very tedious process, and so a further (rather gross) assumption is made that the depths ("h") and widths ("W") of all shelves are roughly the same. Miller's values have hence been divided by the shelf lengths "L") and used as estimators of the tidal dissipation levels in so far as they effect the "$h/u_3$" parameter. Hence high levels of "E/L" indicate areas of low "$n/u_3$" or areas where stratification may be removed by tidal mixing, giving rise to frontal formation.

The computations were performed by measuring shelf lengths on Miller's map (similar to Figure 1), and applying the appropriate scale for that latitude to derive "L" .Some modifications of Miller's values was made using more recent data(Choi, 1980 (Ryuku Islands); Flather, 1976 ( North West European Shelf), Sunderman, 1977 (Bering Sea)): and data for the Cook Strait was added(Bowman, Kibblewhite and Ash, 1980). The results are shown in Figure 1, and TABLE 1. The values of "E/L" have been ranked in descending magnitude (the Okhotsk Sea has the largest value, and is ranked "o"). The numbers shown in the Figure 1, for each region, are the section number (as given in the table),'followed by the rank (in brackets).

There are several consistencies in Miller's paper, in which cases "best guesses" of the correct values have been made. Some sections of "zero" dissipation were present in Miller's map but not in his table - these have been denoted by "(-)" in Figure 1.

We know that "h/u*3*" frontal effects are just apparent in the Gulf of St. Lawrence, a relatively low dissipation area (Pingree and Griffiths, 1980). We may hence regard this as roughly indicative of the lower limit of energy dissipation necessary for the occurrence of frontal structures - hence all regions of rank less than about 23 may exhibit tidal fronts. Examination of Figure 1 indicates the following areas that fulfil this criterion:

(a) The North West European shelf(2), the gulf of St. Lawrence,(22), the Bering sea (20), the bay of Fundy and gulf of Maine(9) and the Cook Strait (4),where tidal fronts have been observed(rank shown in brackets).

(b) Most of the Pacific margin North of the Equator.

(c) The north and East margins of the Indian Ocean.

(d) Australia to he Lesser Sunday islands.

(e) The south-east and north-east coasts of South America.

(f) The near-Arctic and Arctic areas of the Hudson Strait, the Davis Strait and Norway to Svaldbard, all of which must fall into a special category.

It would appear rather ironic that of the shelf regions of the world that have received most attention form oceanographers - the shelves of North West Europe, the U.S.A., Western South America and West Africa, only the former satisfies the above criterion.

An alternative way of looking at the importance of tidal dissipation is to compare the mixing effects of tidal currents and winds. It can be shown (Simpson and Bowers, 1981) that a tidal stream of surface amplitude "$u_s$" at Springs is equivalent to a root mean cubed wind of

$$9.49\ u_s \qquad (17)$$

Hence for a typical wind of 5 metres per second, a tidal stream of surface Springs amplitude 0.53 metres per second exerts an equivalent mixing effect. Hence for a front to be dominated by tidal effects, we require tidal currents of order 1 metre per second. This also agrees with the criterion derived form actual frontal values of the stratification parameter(equation 14).

## THE BUOYANCY SUPPLY TO SHELF SEAS

### (a) Surface Heating

The flux of heat through the surface of the sea is by no means determined simply by the rate of solar radiation and the meteorological conditions, since the sea surface temperature plays an important role in the mechanisms involved in dissipating heat (back radiation, and "diffusive" and evaporative heat loss). An isolated lake, continually heated by the sun and atmosphere, will eventually reach an equilibrium temperature at which there is no total heat flux (expect for a very small geothermal heat flux upwards). If we know the sea surface temperature, then methods are available for estimating the various flux terms, in order to derive the total heat flux through the surface. An alternative approach is to look at the temperature history of a column of sea water and to thereby derive the total heat supplied to that column over a given period. This latter method takes account of the advection and diffusion of heat into the column from the surrounding sea water, but unfortunately does not tell us where in the water column the heat is introduced (as noted in Section 2, this must be known if we are able to computer the rate of input of potential energy to the system) and we are therefore forced to assume that the heat enters at the sea surface.

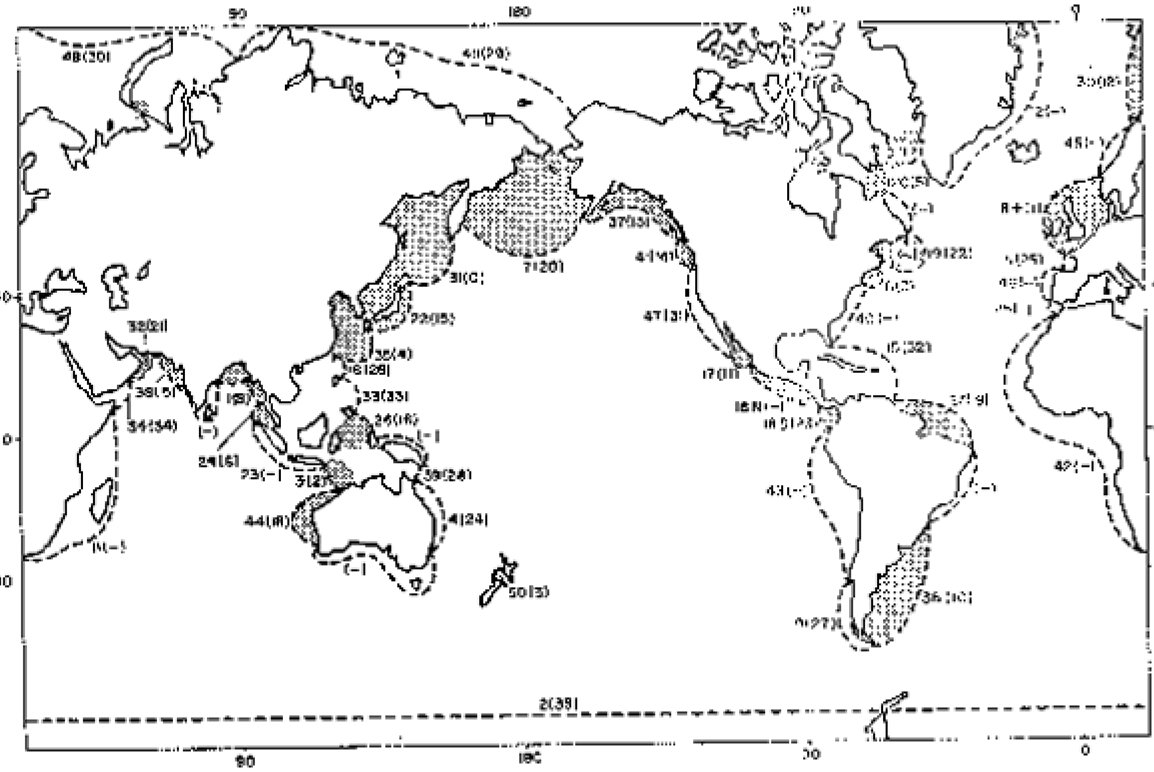
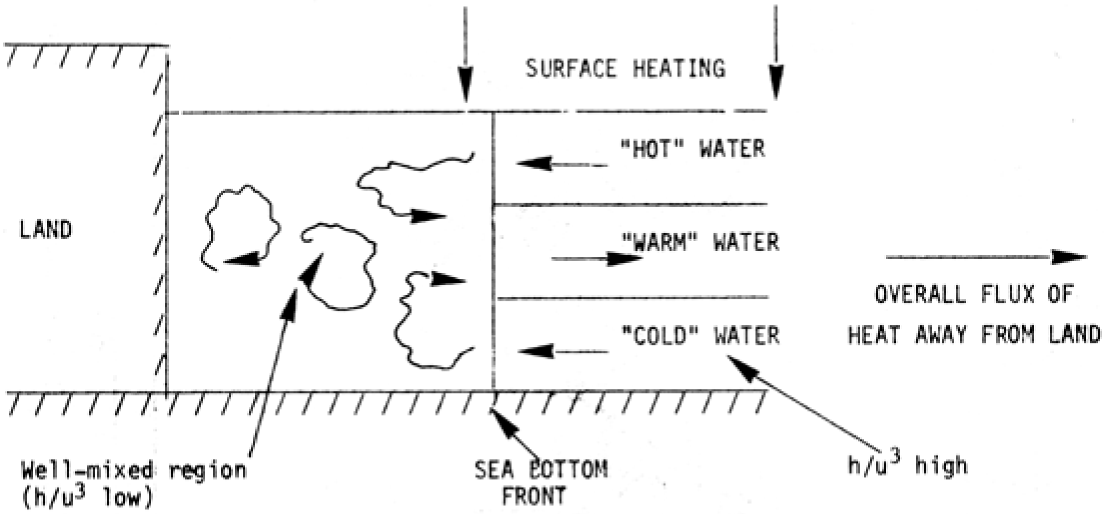



Fig. 1. Tidal dissipation of shelf areas (from Miller, 1966, and others).

Using estimates of the various heat flux terms at the sea surface, Hunter (1982) deduced a total flux of order 100 Joules per square metre per second for the northern part of the Arabian Gulf during the period of maximum heating. From estimates based on the temperature history of a water column of the North West European Shelf, Simpson and Bowers, 1981, used a maximum heating rate of 100 Joules per square metre per second in their modelling works. Strokina, 1967, 1969, used this latter approach to produce seasonal maps of the heat flux to the upper layers of the world's oceans. While these are not really appropriate to the shelf areas, due to the strong dependence of the heat flux on sea surface temperature and local meteorology, it is worth noting that for the southern hemisphere the positive heating flux is always less than about 160 Joules per square metre per second. It would hence appear that there i not a wide range in the values of maximum heating flux over the sea. For a factor of 2 change in buoyancy (or heat) flux, the critical stratification parameter (equations (7) to (12) changes by 0.3 For the North West European shelf, the stratification parameter changes by about I in 100 kilometres (Pingree and Griffiths, 1978), so a factor of 2 change in buoyancy input would be expected to move the fronts by only about 30 kilometres. Frontal position hence does not depend very strongly on the exact rate of supply of buoyancy.

In non-tropical areas, the heat flux to shelf seas generally shows a well defined annual periodicity. For the North West European shelf, it is positive from mid-March to mid-September (Simpson and Bowers, 1981), and significant stratification exists from April to November (Simpson, Hughes and Morris, 1977). However, the frontal positions are only approximately constant from early June to late August (Simpson, 1981). There would seem to be no reason why these timings should not apply approximately to the rest of the non-tropical northern hemisphere, and, with a shift of 6 months to the non-tropical southern hemisphere.

For tropical areas, where the seasonal change in heating rate over shelf seas is small, it is necessary that there be some mechanisms for the removal of buoyancy if a steady stratification is to develop (as noted in Section 2). A possible system is shown schematically below




The horizontal density gradients induced would drive the circulation necessary to maintain a steady state. For larger systems, Coriolis accelerations would become important and the above two-dimensional circulation pattern would become three- dimensional, with a component of current in a longshore direction.

TABLE 1.TIDAL DISSIPATION OF SHELF AREAS (from Miller, 1966 and others)

| Region | NO | Dissipation (ergs/s.×$10^{-17}$) | Dissipation Per Unit Length (ergs/cm./s./×$10^{-9}$) | Rank | *=Region of Potential Tidal Effects |
|---|---|---|---|---|---|
| Andaman Sea to 21° N | 1 | 6.5 | 5.5 | 8 | * |
| Antarctica | 2 | 0.1 | 0.006 | 35 | |
| Australia to Lesser nda Islands | 3 | 15 | 12.4 | 2 | * |
| Barrier Reef | 4 | 2.4 | 0.96 | 24 | |
| Bay of Biscay | 5 | 0.4 | 0.76 | 25 | |
| lf of Maine | 6 | 2.3 | 4.9 | 9 | * |
| Bering Sea | 7 | 2.9 | 1.4 | 20 | * |
| N.W.European shelf | 8+ | 21.48 | 14.2 | 1 | * |
| Chile | 9 | 0.4 | 0.28 | 27 | |
| Davis Strait etc. | 10 | 2 | 1.9 | 17 | |
| East Africa | 11 | 0 | 0 | - | |
| Eastern Greenland | 12 | 0 | 0 | - | |
| Florida to Trinidad | 15 | 0.3 | 0.11 | 32 | |
| Formosa to Luzon | 16 | 0.5 | 0.65 | 26 | |
| Gulf of California | 17 | 4 | 3.2 | 11 | * |
| Gulf of Panama | 18N | 0 | 0 | - | |
| Gulf of Panama | 18S | 0.6 | 0.99 | 23 | * |
| Gulf of St. Lawrence | 19 | 0.8 | 1.0 | 22 | * |
| Hudson Strait | 20 | 12 | 10.7 | 5 | * |
| Japan Islands | 22 | 4.3 | 2.3 | 15 | * |
| Java to Sumatra | 23 | 0 | 0 | - | |
| Malacca Strait | 24 | 7 | 7.0 | 6 | * |
| Mediterranean | 25 | 0 | 0 | - | |
| Mindanao to N. Guinea | 26 | 2 | 2.0 | 16 | * |
| N.E. coast of S. America | 27 | 5 | 1.6 | 19 | * |
| North Bay of Bengal | 29 | 6 | 6.2 | 7 | * |
| Norway to Svaldbard | 30 | 3.2 | 3.0 | 12 | * |
| Okhotsk Sea | 31 | 21 | 14.6 | 0 | * |
| Oman-Persian Gulf | 32 | 1.6 | 1.2 | 21 | * |
| Philippines | 33 | 0.1 | 0.083 | 33 | |
| Red Sea | 34 | 0.2 | 0.080 | 34 | |
| Ryukyu Islands | 35 | 11.96 | 11.3 | 4 | * |
| S.E. coast of S. America | 36 | 13 | 3.9 | 10 | * |
| Southern Alaska | 37 | 5 | 2.5 | 13 | * |
| Southern India | 38 | 4 | 2.3 | 15 | * |
| Torres Strait | 39 | 0.3 | 0.25 | 28 | |
| U.S. east coast | 40 | 0 | 0 | - | |
| Vancouver, Juan de Fuca | 41 | 1.6 | 2.4 | 14 | * |
| West Africa | 42 | 0 | 0 | | |
| West S. America uator to 42° S | 43 | 0 | 0 | | |
| Western Australia | 44 | 4.2 | 1.8 | 18 | * |
| Western Norway | 45 | 0 | 0 | | |
| Western Spain | 46 | 0 | 0 | | |
| Western US to Baja, CA | 47 | 0.4 | 0.13 | 31 | |
| Svaldbard to Taimyr | 48 | 0.3 | 0.16 | 30 | |
| Taimyr to Pt. Barrow | 49 | 0.6 | 0.19 | 29 | |
| Cook Strait | 50 | 2.73 | 11.4 | 3 | * |

(b) Supply or Removal of Fresh Water

In buoyancy terms, the addition of 1 joule of heat is roughly equivalent to $3\times10^{-9}$ cubic metres of fresh water. Hence a surface heat input of 100 Joules per square metre per second has the same buoyancy effect as the addition of $3\times10^{-9}$ cubic metres per square metre per second of fresh water. This is the equivalent of a river the size of the Mersey, England ,discharging 50 cubic metres per second over an area of 170 square kilometres(e.g., a square of side 13 kilometres), or a rainfall equivalent to $3\times10^{-7}$ metres per second or about 10 metres per year ( a large figure by global standards). Hence a river may input a significant amount of buoyancy(compared with surface heating) in the region around its mouth 9within a few tens of kilometres), but only over short periods could rainfall over the sea input a comparable amount of buoyancy.

During evaporation of water from the sea surface( which is especially important in tropical areas), latent heat is absorbed at a rate of about $2\times10^{9}$ joules per cubic metre of water. This cubic meter of water is equivalent to about $3\times10^{8}$ Joules of heat supply in buoyancy terms. Hence from the point of view of the buoyancy supply, the effect of evaporation is mainly to absorb latent heat, thereby cooling the water and adding the negative buoyancy(at a rate of $2\times10^{9}$ Joules per cubic metre). The loss of fresh water is only equivalent to about 15 per cent of this buoyancy flux (the equivalent of $3\times10^{8}$ Joules per cubic metre).

Over most of the world's oceans, the evaporation rate roughly cancels the precipitation rate(of order 1 metre per year) 9Budyko, 19740, so the previous comments concerning the general insignificance of rainfall apply also to evaporation. However, in tropical areas, evaporation may exceed precipitation and become a significant source of negative buoyancy - for example, the average evaporation rate over the Arabian Gulf of order 1.4 metres per year(Privett, 1959), compared with a rate of precipitation of 1.4 metres per year( Hydrographer of the Navy, 1967), the difference being equivalent in buoyancy terms to a heat loss of about 13 joules per square metre per second. Even though this evaporation rate is not particularly high, it is more likely than a rainfall to produce local areas of mixed and stratified waters for two reasons:

(i) Rainfall is independent of sea surface temperature and so does not have well-defined localized distributions over the sea. Evaporation, on the other hand is often high in shallow coastal regions due to lower relative humidity and (in the summer) to higher sea surface temperatures near the coast.

(ii) As noted previously, associated with evaporation is an absorption of latent heat equivalent, in buoyancy terms, to about 7 times the fresh water loss.

The dominant buoyancy sources for shelf seas are hence surface heating, river runoff and evaporation. It has been shown above the there are circumstances by which any of these can provide sufficient buoyancy for the formation of frontal structures.

## CONCLUSIONS

Tidal shelf sea fronts are associated with regions of relatively high dissipation, areas which are indicated by rank in Figure 1.

Stratification may be induced by surface heating, river runoff or evaporation, and the majority of known tidal frontal structures are associated with seasonal changes of surface heating in non-tropical areas. However, we should not discount tropical areas as to possible sites for tidal fronts, generated by any of the three buoyancy sources, since in the estuaries of the world we have good examples of quasi0steady density stratification being maintained by the interaction of positive buoyancy (fresh water) and negative buoyancy ("ocean" water) under the control of tidal and wind-driven mixing.

For buoyancy input by seasonal heating in the non-tropical northern hemisphere, stratification probably exists from April to November, with stable frontal positions from early June to late August. In the southern hemisphere one would expect these times to be shifted by 6 months.

The characteristic dimensions of fronts and eddies are quite diverse, ranging from short scales of meters to kilometres, corresponding to scales of relevance to larval fish, fish populations, and the aggregation of fishing activities based on "local" resource aggregations. Our knowledge of these events, processes and the dependence of fishery activities related to them needs to be expanded, certainly through more varied scale studies on the processes promoting them in order to better locate them in time and space. It follows that detailed studies of the biological milieu associated with the various features will yield insights into important processes, particularly related to fish reproduction, productivity and energy transfer, and fishery effectiveness measures.

## REFERENCES


Allen, J.S. and R.L. Smith. 1981. On the dynamics of wind-driven shelf currents. Phil.Trans.R.Soc. Lond. A302:617–634.

Alvarino, A. 1980. The relation between the distribution of zooplankton predators and anchovy larvae. CALCOFI Reports XXI. (Also ICES, Early Life History Meeting, Woods Hole, April 1979, poster no.21).

Anderson, K.P. and E.Ursin. 1977. A multispecies extension of the Beverton and Holt theory of fishing, with accounts of phosphorus circulation and primary production. Meddr.Damm.Fisk-og Havunders, N.S. 7:319–435.

Anon. 1981. Circulation and fronts in Continental Shelf seas (conference proceedings). Phil.Trans.R. Soc.Lond. A302:515–689.

Bakun, A., J. Beyer, D. Pauly, J.G. Pope and G.D. Sharp. 1982. Ocean Sciences in relation to living resources. Can.J.Fish.Aquat.Sci. 39(7):1059–1070.

Bakun, A. and R.H. Parrish. 1981. Environmental inputs to fishery population models for eastern boundary current regions. pp. 67–104. In Workshop on the effects of environmental variation on the survivl of larval pelagic fisher (G.D. Sharp, ed.). IOC Workshop Rep. 28. IOC/UNESCO, Paris.

Baronov, F.I. 1918. On the questionof the biologicl baiss of fisheries. Nauch.issledov.iktiol, Inst.Izv.I. (1):81–128, Izv.ryb.i. nauch.isseldov. 1(1) Moscow.

Beardall, J., G.E. Fogg, P. Foster, I. Miller, C.P. Spencer and D. Voltolina. 1978. Biol-Contemp. 5:163–175.

Beverton, R.J.H. and S.J.Holt. 1957. On the dynamics of the exploited fish populations. Fish.Invest., Lond. Ser.2., 19:533 p.

Beyer, J. and P.Sparre. 1983. Modelling exploited fish stocks. In Application of Ecological Modelling in Environmental Management (S.E. Jorgensen, ed.). Elsevr Scientific Publishing Company, Amsterdam.

Bowman, M.J., A.C. Kibblewhite and D.E. Ash. 1980. M2 tidal effects in Greater Cook Strait, New Zealand, J.Geophys.Res. 85(C5):2778–2742.

Budyko, M.I. and D.H. Miller (eds). 1974. Climate and Life. Academic Press. New York. 508 p.

Chapman, W.M. 1972. The application of oceanography to the development and management of ocean fisheries. pp.13–21. In Progress in Fishery Science. Fifteenth Anniversary Celebration Symposium (R.W. Moore, ed.). University of Washington Press. Univ. of Washington Publications in Fisheries, New Series, Vol.5.

Choi, B.H. 1980. A tidal model of the Yellow Sea and the Eastern China Sea, Korean Ocean Research and Development Institute. Report 80–02.

Cushing, D.H. 1971. The dependence of recruitment on parent stock in different groups of fishes. J.Cons.int.Explor.Mer. 33:340–362.

Cushing, D.H., 1972. The production cycle and numbers of marine fish. Symp.Zool.Sco., London. 29:213–232.

Dooley, H.D. 1978. The role of axially varying vertical mixing along the path of a current in generating phytoplankton production. Phil.Trans.R.Soc.Lond. A302:649–661.

Fasham, M.J.R. 1978. The statistical and mathematical analysis of plankton patchiness. Oceanogr. Mar.Biol.Ann.Rev, 16:43–79.

Fearnhead, P.G. 1975. On the formation of fronts by tidal mixing around the British Isles, Deep-Sea Res. 22:311–321.

Flather, R.A. 1976. A tidal model of the Northwest European continental shelf. Mem.Soc.R.Sci.Liege, 6ee serie, X:141–164.

Foster, P., G. Savidge, G.M. Foster, D.T.E. Hunt and L.B. Pugh. 1976. Multivariate analysis of surface water characteristics in the summer regime of the Western Irish Sea. J.Exp.Mar.Biol.Ecol. 25(2):171–185.

Garcia, S. (in press). The stock-recruitemetn relationship in shrimps: reality or artefacts and misinterpretation. Oceanogr.Trop.

Garrett, C.J.R., J.R. Keeley and D.A. Greenberg. 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine. Atmosphere-Ocean. 16(4):403–423.

Gieske, W.W.C., G.W. Kraay and M.A. Baars. 1979. Current 14C methods for measuring primary production: gross understimates in oceanic waters. Netherlands J. of Sea.Res. 13(1):58–78.

Glantz, M.H. and J.D. Thompson (eds.) 1981. Resource Management and Environmental Uncertainty, Lessons from coastal upwelling fisheries. John Wiley and Sons, New York, Chichester, Brisbane, Troronto. 491 p.

Graham, M. 1935. Modern theory of exploiting a fishery, and applications to North Sea trawling. J.Cons.int.Explor.Mer. 10:264–274.

Grainger, R.S.R. 1980. Herring abundance off the west of Ireland in relation to oceanographic variation. J.Cons.int.Explor.Mer. 38(2):180–188.

Grall, J.R., P. Le Corre, J. Le Fevre, Y. Marty and B. Fournier. 1980. Oceans. 6:235–274.

Gregg, M.C. 1980 Microstructure patches in the thermocline. J.Phys.Ocean. 10:915–943.

Harding, D., J.H. Nichlos and A.R. Folkard. 1978. Studies on planktonic fish eggs and larvae in relation to environmental conditions in the west central North Sea. Annls.Biol. 33:62–69.

Hardy, A.C. 1924. The herring in relation to its animate environment, Part 1. The food and feeding habits of herring. Fish.Innvest.Lond., Ser. II, 7, 53 p.

Hennemuth, R.C., J.E. Palmer, B.E. Brown. 1981. A statistical description of recruitment in eighteen selected fish stocks. J.Northw.Atl.fish.Sci. 1:101–111.

Hiort, j. 1914. Fluctuations in the year classes of important food fishes. IJ.du Conseil. (1):5–38.

holligan, P.M. 1981. Biological implications of fronts on the Northwest European continental shelf. Phil. trans.R.Soc,Lond. A302:547–562.

Houde, E.D. 1974. Effects of temperature and delayed feeding on growth and survival of larvae of three species of subtropical marime fishes. Mar.Biol. 26:271–285.

Houde, E.D. 1975. Effects of stocking density and food density on survival, growth and yield of laboratory-reared larvae of sea bream Archosargus rhomboidalis (L) (Sparidae). J.Fish.Biol. 7:115–127.

Houde, E.D. 1978. Critical food concentrations for larvae of three species of subtropical marine fishes. Bull-Mar.Sci. 28:395–411.

Houde, E.D. and R.C. Schekter. 1981. Functional and developmental responses of fish larvae to varying prey concentrations. Symposium on Early Life History of Fish, Woods Hole, Massachusetts, April 1979. Repp.P.-v.Réun.Cons.int.Explor.Mer. 178.

Hunter, J. 1982. Tidal and stratification/mixing models of Kuwait waters, Kuwati Bulletin of Marine Science (in press).

Hunter, J.R. 1982. The feeding ecology of marine fish larvae. In J.E. Bardach (ed.), The Physiological and Behavioural Manipulation of Food Fish as Production and Management Tools. International Center for Living Aquatic Resources Management, Manila.

Hydrographer of the Navy. 1967. Persian Gulf Pilot. 11th Edition. NP63, London.

Illes, T.D. and m.Sinclair. 1982. Atlantic herring: stock discretensess and abundance. Science. 215(4533):627–633.

James, I.D. 1981. Fronts and shelf-ciculation models. Phil.Trans.R.Soc.Lond. A302:597–604.

Jones, R. and W.B. Howell. 1974. Some observations on the population dynamics of the larval stage in the common gadoids. pp. 87–102. In the Early Life History of Fish (J.H.S. Blaxter, ed.). Springer-Verlag, New York.

Laevastu, T. and H.A.Larkins. 1981. Marine fisheries ecosystem: its quantitative evaluation and management. Fishing News Books Ltd., Farnham. 159 p.

Lasker, R. 1975. Field criteria for survival of anchovy larvae: the relation between inshore cholorophyll maximum layers and successful first feeding. Fish.Bull.U.S. 73:453–462.

Lasker, R. 1978. Ocean variability and its biological effects-regional review-northeast Pacific. Rapp.P.-v.Réun.Cons.int.Explor.Mer. 173:168–181.

Laurec, A. and J.-C. Le Guen. 1981. Dynamique des populations Marines Exploites: tome 1, concepts et modeles. Pub.du Centre National pour L'Exploitation des Oceans, CNEXO, Brest. 115 pp.

Laurence, G.C. and J.E. Beyer. 1981. A stochastic dynamic model of growth and mortality in winter flounder larve (Pseudopleuronectes americanus) reared in the laboratory under experimental conditions. Symposium on Early Life History of Fish, Woods Hole, Massachusetts, April 1979 Rapp.P.-v.Réun.Cons.int.Explor.Mer. 178.

MacCall, A.D. 1981. The consequence of cannibalism in the stock-recruitment relationship of planktivorous pelagic fishes such as Bngraulis. p. 201–217. IOC Workshop Report No. 28. (G.D. Sharp, ed.). IOC/UNESCO, Paris.

Mann, K.H. 1982. Ecology of coastal waters: a systems approach. Studies in Ecology, Volume 8 Blackwell Scientific Publications. Oxford, London, Edinburgh, Boston, Melbourne. 322 pp.

Miller, G.R. 1966. The flux of tidal energy out of the deep oceans. J.Geophys.Res. 71(10):2485–2489.

Nihoul, J.C.J. (ed.). 1982. Hydrodynamics of semi-enclosed seas. Elsevier Scientific Publishing Company, Amsterdam, Oxford, New York. 555 p.

Owen, R.w. 1980. Eddies of the California current system: physical and ecological characteristics. In the california Islands (D.M. Power, ed.). Santa Barbara Mus.Nat.History (Calif.).

Owen, R.w. 1981. Patterning of flow and organisms in the larval anchovy enviornment. pp. 176–200. In IOC Workshop Report No. 28. (G.D. Sharp, ed). UNESCO, Paris.

Owen, R.w. 1982. Microscale plankton patchiness in the larval anchovy enviornment. Rapp.P.-v.Réun.Cons.int.Explor.Mer. 178:364–368.

Parrish, R.H., C.S. nelson and A. Bakun, 1981. Transport mechanisms and reproductive success of fishes in the California Current. Biol.Oceanogr. 1(2):175–203.

Pauly, D. (Draft). Fish Production Dynamics in Tropical Waters: International Center for Living Aquatic Resources Management, Manila.

Petersen, C.G.J. 1984. On the biology of our flatfishes and on the decrease of our flatfish fisheries. Rep.Dan.biol.Stn. IV. 147 pp.

Pingree, R.D. and D.K. Griffiths. 1977. The bottom mixed layer on the continental shelf. Estuar.Coast.Mar.Sci. 5:399–413.

Pingree, R.D. and D.K. Griffiths. 1978. tidal fronts on the shelf seas arount the British Isles. J.Geophys.Res. 83(C9):4615–4622.

Pingree, R.D. and D.K. Griffiths. 1980. A numerical model of the M2 tide in the Gulf of St. Lawrence, Oceanologica Acta. 3(2):221–225.

Pingree, R.D., P.M. Holligan and G.T. Mardell. 1978. The effects of vertical stability on phytoplankton distributions in the summer on the northwest European continental shelf. Deep Sea Res. 25:1011–1028.

Pingree, R.D., P.M. Holligan and G.T. Mardell. 1979. Phytoplankton growth abd cyclonic eddies. Nature. 278:245–247.

Pingree, R.D., P.R. Pugh, P.M. Hollian and G.R. froster. 1975. Nature. 258:672–677.

Privett, D.W. 1959. Monthly charts of evaporation from the N. Indian Ocean (including the Red Sea and the Persain gulf). quart.J.Roy.Met.Soc.(Lond.). 85:424–428.

Reid, J.L., E. Brinton, A. Fleminger, E.L. Vernick and J.A. McGowan. 1978. Ocean circulation and marine life. pp. 65–130. In Advances in Oceanography. Plenum Press, New York.

Richards, F.A. (ed.0. 1981. Coastal Upwelling. American Geophysical Union, Washington, D.C. 529 pp.

Ricker, W.E. 1954. Stock and recruitment. J.Fish.Res.Bd.Canada. 11:559–623.

Ricker, W.E. 1958. handbook of computations for biological statitics of fish populations. Bull.Fish.Res.Bd.Canada. No. 119.

Rosenthal, H. 1970. Anfutterung und Wachstum der Larven und Jungfische des Hornhechts Belone belone. Helgolaender Wiss.Meeresuntersuch. 21:320–332.

Saetersdas, G. 1980. A review of past management of some pelagic stocks and its effectiveness. Rapp.P.-v.Réun.Cons.int.Explor.Mer. 177:505–512.

Savidge, G. 1976. A preliminary study of the distribution of chlorophyll A in the vicinity of fronts in the Celtic and Western Irish Seas. Estuar.Coast.Mar.Sci. 4:617–625.

Savidge, G. and P. Foster. 1978. Plankton biology of a front in the Celtic Sea. Nature, London. 271:155–156.

Schumacher, J.D., T.H. Kinder, D.J. Pashinski and R.L. Charnell. 1979. A structural front over the Continental Shelf of the Eastern Bering Sea. J.Phys.COceanogr. 9:79–87.

Sharp, G.D. 1981a. Report of the Workshop on the Effects of Environmental Variation on Survival of Larval Pelagic Fishes. pp. 1–47. In Intergovernmental Workshop Series, No. 28 (G.D. Sharp, ed.). UNESCO, Paris.

Sharp, G.D. 1981b. Colonization: modes of opportunism in the ocean. pp. 125–148. In Workshop on the Effects of Environmental Variation on the Survival of Larval Pelagic Fishes. 20 April-5 May 1980. Lima, Peru. (G.D. Sharp. ed.). IOC Workshop Report series No. 28. IOC/UNESCO, Paris.

Sharp, G.D. 1981c. Report of the expert consultation on the research status and potential of cod rearing in the North Atlantic. Organized in collaboration with the Svanøy Foundation, Svanøy, Norway, 2–9 August 1981. 12 pp.

Sharp, G.D. (ed.). 1981d. Intergovenmental Oceanographic Commission Workshop Report No. 28. Workshop on the Effects of Environmental Variation on the Survival of Larval Pelagic Fishes. 20 April-5 May 1980. Lima, Peru. UNESCO, Paris. 323 p.

Shepherd, J.G., J.G. Pope and R.D. Cousens. 1982. Variations in fish stocks and hypotheses concerning their links with climate. Mini Symposium ICES CM 1982/GEN:6. 22 pp. plus tables and figures.

Simpson, J.H. 1981. The shelf-sea fronts: implications of their existence and behaviour. Phil.Trans.R.Soc.Lond. A:302:531–542.

Simpson, J.H. and D. Bowers. 1979. Shelf-sea fronts' adjustments revealed by satellite IR imagery. Nature. 280(5724):648–651.

Simpson, J.H. and D. Bowers. 1981. Models of stratification and frontal movement in shelf seas. Deep-Sea Res. 28A(7):727–738.

Simpson, J.H. and J.R. Hunter. 1974. Fronts in the Irish Sea. Nature. 250:404–406.

Simpson, J.H., C.M. Allen and N.C.G. Morris. 1978. Fronts on the Continental Shelf. J.Geophys.Res. 83(C9):4607–4614.

Simpson, J.H., D.G. Hughes and N.C.G. Morris. 1977. The relation of seasonal stratification to tidal mixing on the Continental Shelf. A Voyage of Descovery. Pergamon, pp. 327–340 (Ed. M. Angle).

Simpson, J.H., D.J. Edelston, A. Edwards, N.C.G. Morris and P.B. Tett. 1979. The Islay front: physical structure and phytoplankton distribution, estuaine and coastal. Mar.Sci. 9:713–726.

Smith, P.E. and R. Lasker. 1978. Position of larval fish in an ecosystem. Rapp.P.-v.Réun..Cons.int. Explor.Mer. 173:77–84.

Steele, J.H. 1974. The structure of marine ecosystems. Blackwell Scientifc Publications. Oxford, London, Edinburgh, Melbourne. 128 pp.

Strokina, L.A. 1967. Determination of variation in the heat content of the oceans. Tr. Gl. Geofiz. Observ. 209:58–69.

Strokina, L.A. 1969. Variation in the heat content of the oceans of the Southern Hemisphere Tr.Gl.Geofiz.Observ. 249:58–64.

Sunderman, J. 1977. The semi-diurnal principal lunar tide M2 in the Bering Sea, Deutsche Hydrograph. Zeitschr. J. 30(3)93–93–101.

Sverdup, H.O. 1952. Some remarks on the place of hydrography in fisheries research. Rapp. P- v. Réun. Cons.int.Explor.Mer. CXXXI.p.7.

Sverdup, H.O. 1955. The place of physical oceanography in oceanographic research. J. Mar Res. 14(4):287–294.

Szekielda, K.-H., D.J. Suszkowski and P.S. Tabor. 1977. Skylab investigation of the upwelling off the northwest coast of Africa. J. Cons. int. Explor. Mer. 37(3):205–213.

Theilacker, G. and K. T. Dorsey. 1981. Larval fish diversity, a summary of laboratory and field research. p. 105–142. In IOC Workshop Report No. 28 (G.D. Sharp, ed.). IOC/UNESCO, Paris.

Thomasson, E. M. 1981. Study of the Sea: the development of marine research under the auspices of the International Council for the Exploration of the Sea. Fishing News Books Ltd., Farnham. 256 p.

Voronina, N. M. 1978. Variability of ecosystems. pp. 221–244. In Advances in Oceanography (H. Charnok and G. Deacon, eds). Plenum Press, New York.