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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Summing-Up [and Discussion]

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Summing-up

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The various contributions to the Discussion Meeting are related to general aspects of the subject, and some topics requiring further investigation are identified. These include the evolution and stability of fronts, and the processes by which cross-frontal and cross-shelf mixing take place. The relation of physical processes to the growth of phytoplankton in the vicinity of fronts needs further study. Among points relating particularly to the northwest European shelf seas are the influence of the oceanic flow at the shelf edge and the nature of the band of cold water, with its zone of enhanced biological activity, that occurs over the Celtic Sea shelf break in summer.

Introduction

In this summing-up I shall not attempt to review all the papers presented at this Discussion Meeting but shall try to relate the various contributions to general aspects of the subject. In this way it is hoped to pick out some points that need further discussion and to suggest some ideas for future work.

The subject of the Discussion has been circulation and fronts in continental shelf seas, but three distinct regions are involved. These are the deep ocean, the slope or shelf break and the continental shelf itself. It is appropriate, therefore, to refer briefly to the role played by the first two of these before considering in more detail the process operating on the continental shelf.

Influence of the deep ocean

The deep ocean is involved as a possible driving force for the circulation on the shelf, the interaction taking place across the shelf break. The importance of this off the northeast coast of the U.S.A. was shown by Professor Mooers, who described how the Gulf Stream, with its meanders and eddies, influenced flow on the adjacent shelf. The long-term flow to the southwest along the shelf is probably caused by a longshore pressure gradient, associated with the Gulf Stream and the slope water gyre. The mean oceanic flow on the eastern side of the North Atlantic is much weaker than that on the west, and the extent to which it influences the circulation on the northwest European shelf has not yet been established. There are slow long-term flows to the north off the west of Ireland and through the Celtic Sea and Irish Sea, but whether these are maintained by a pressure gradient from south to north along the shelf break or by processes acting locally on the shelf does not appear to have been determined. Stronger flows occur into the North Sea through the Orkney–Shetland Channel and along the western slope of the Norwegian Trough, with an outflow in the Norwegian Coastal Current, as discussed by Mr Dooley and Professor Mork. The magnitude of these flows fluctuates from month to month and year to year but it is not clear to what extent these fluctuations are influenced by the deep water flow at the shelf break.

The ocean also influences conditions on the slope and shelf through the tides. A fraction of the energy of the incoming barotropic tide from the ocean is used in generating internal tides at the continental slope and these may have a significant, although as yet unquantified, effect on mixing at the shelf break. Most of the tidal energy crossing the slope, however, is used in driving the barotropic tides on the continental shelf. We are not concerned here with the form of the tidal movements themselves but with their effect on the shelf circulation, through the action of bottom friction and vertical mixing. This effect is likely to be particularly important on the northwest European shelf, since it is estimated that 12.5 % of the world's total dissipation of tidal energy takes place on the relatively small area of this shelf.

The shelf break

From the oceanic side, the shelf-break region has been described as a boundary layer of the deep sea circulation. Here we are more concerned with its effect on circulation on the shelf. As well as being the source area of internal tides, the shelf break probably plays a role in the generation of trapped waves, forced by the ocean circulation.

An important feature of the shelf break off the northeast coast of North America is the occurrence, especially in the winter, of a sharp front between the coastal water and the slope water, as described by Professor Mooers. Such a pronounced front does not appear to occur at the shelf break off northwest Europe. There are several possible explanations for this: (*a*) the deep water flow, and presumably its action on the shelf water, is much weaker than on the North American side of the Atlantic; (*b*) there is a smaller volume of freshwater influx and a smaller seasonal range of heat flux on this side; (*c*) the continental shelf is considerably wider, on average, on the European side so that fronts may tend to form on the shelf rather than at the shelf break.

A notable feature of the Celtic Sea shelf break is the band of cold surface water associated with an enhanced phytoplankton population, described by Dr Pingree, which occurs in the summer months and extends from southwest of Ireland to the Bay of Biscay. This appears to be a zone with fronts separating it from the warmer water on either side. It has been suggested that it is: (*a*) an example of shelf-break upwelling, which is known to occur in other areas and is a feature of several theoretical models; (*b*) a region of increased vertical mixing, thus reducing the temperature contrast between the surface and subsurface water; (*c*) a surface divergence of flow, due to a marked change in friction at the thermocline, the density gradient in which is observed to be appreciably sharper on the shelf side of the break than on the ocean side. Further study is needed to distinguish between these processes, which may interact in different ways with the biological productivity in the zone.

The continental shelf

Turning to the continental shelf itself, some basic dynamical features of the circulation were described by Dr Csanady. Here the wind-driven circulation appears to be of primary importance. A rapidly increasing body of observational data is becoming available and this can be set against an extensive background of dynamical theory. Dr Allen has described in detail the currents in three upwelling areas, bringing out the differences between them and the varying relative magnitudes of terms in the dynamical equations relating to them. The effects of wind on

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currents in other shelf areas have been considered by Professor Mooers and Professor Mork. Synoptic-scale events, on time-scales of the order of two to six days, associated with the passage of weather systems, appear to be the most significant. Longer period circulation patterns, on the monthly or seasonal scale, are probably very largely the residual effects of synoptic-scale events.

It seems to be well established that shelf waves play an important part in the response of shelf waters to wind-forcing, particularly in the propagation of effects along the shelf and probably in the longer term residual response. This is an area where the interaction between observations, of current and coastal sea level, and theory has been very fruitful.

The second main type of forcing in shelf waters is that due to density gradients, arising from the influx of river water from the coasts. The interaction between circulation and mixing is important here because it is on the shelf, or at the shelf break, that fresh water, with its accompanying load of pollutants, becomes mixed with ocean water and flushed from the coastal system. A feature of the density-driven circulation is its longer time-scale, so that although over a few days its effect may be obscured by wind-driven events, it may have a greater effect on monthly or longer time-scales. The valuable role of laboratory experiments in clarifying the physical and dynamical processes involved was shown by Dr Whitehead, who described model experiments on a rotating table dealing with three problems in density-driven circulation relevant to shelf seas. This point was demonstrated further by the film shown by Dr Linden, which illustrated the formation of frontal waves and eddies in a density current, resembling those in the Norwegian coastal current described by Professor Mork.

Fronts

A front may be described as a transition zone between two water masses of differing properties. The fronts observed off the northeast shelf of North America and at the Celtic Sea shelf break have been mentioned. The investigation of fronts appears to have followed two basic lines of approach, designed to answer the following questions: (i) How is a front formed and maintained? (ii) What are the properties of a front, including its physical, chemical and biological effects?

The evolution of a front depends, in general, on convergence or divergence in the current field and on processes acting locally to modify properties such as the temperature, salinity and density of the water masses. The simplest fronts to consider are the structural or tidal fronts discussed by Dr Simpson, which arise from spatial differences in the effects of vertical mixing due to tidal friction and wind stress. This is the type of front that appears to occur most commonly, at least during the summer, in northwest European shelf waters. It is the simplest to consider since no pre-existing current field is needed, apart from the tidal currents which are treated purely as a mixing mechanism. One-dimensional theory, leading to the h/U^3 criterion, has been surprisingly successful in explaining the occurrence of mixed and stratified regions, and the location of the fronts separating them. The positions of fronts predicted in this way have been strikingly confirmed by infrared photographs from satellites. A comparison of theoretical predictions with observations enables deductions to be made about the efficiency of wind and tidal mixing, and these may be useful in other contexts.

A one-dimensional theory can account for the differing conditions on the two sides of a front but does not give any information about the front itself. Professor Garrett described a diagnostic model representing the flow near a front as occurring in two vertical cells. The development of

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the flow would soon react on the form of the front, making the one-dimensional theory of formation inadequate, at least in the vicinity of the front itself. The motion at a front has also been studied by Dr James who, in his contribution to this symposium, has shown how instability of the front develops, leading to meandering and eddy formation. Features of this kind have been clearly shown in satellite photographs.

Cross-frontal mixing

An important aspect of the study of fronts is cross-frontal mixing, since this is how the coastal water, with any contaminants that it may contain, passes to the outer shelf and the deep water. Possible exchange mechanisms that have been described by speakers in this Discussion include:

(i) mean flows associated with the frontal structure, which Professor Garrett has indicated to be a major source of cross-frontal transport;

(ii) baroclinic instability of the front, described by Dr James, leading to the formation of eddies that can entrain water on one side of the front and transport it to the other side;

(iii) shear effects, in which gradients of the horizontal velocity interact with vertical mixing to produce an enhanced horizontal transport;

(iv) interleaving of the two water masses which may develop, leading to intrusions bounded by layers of steep temperature and salinity gradients across which double-diffusive processes can operate; indications of interleaving in the Norwegian Coastal Current were mentioned by Professor Mork, and similar interleaving has been observed between the coastal and slope water at the shelf break off the northeast coast of North America.

These mechanisms have been treated theoretically, and estimates can be made of the cross-frontal fluxes that each might produce. It would be interesting to have an assessment of the relative importance of their contributions in different frontal situations. Besides transporting fresh water and contaminants introduced at the coast, cross-frontal fluxes are also responsible for the transfer of heat and of other properties of the water masses, including nutrients and living organisms.

Cross-frontal mixing is an aspect of the wider question of how exchanges between coastal and oceanic waters take place. If fronts are present, the exchanges must take place across them, but cross-shelf mixing occurs in the absence of well-defined fronts. The most likely agency would seem to be horizontal eddies, which are probably present nearly everywhere in the tidal currents. Presumably the wind-driven circulation may also develop inhomogeneities in the flow field, which can give rise to horizontal eddies.

Biological effects

The significance of fronts in the distribution of biological features was reviewed by Dr Holligan. The main interest has been in the abundance of phytoplankton, usually as indicated by the concentration of chlorophyll *a*. Increasing attention is being given to the zooplankton and higher trophic levels and, indeed, the occurrence of concentrations of fish has commonly been regarded as an important indicator of the presence of fronts.

The enhanced growth of phytoplankton in the vicinity of fronts has been studied by several workers. The essential conditions are the presence of nutrients and an adequate level of light for photosynthesis. The degree of vertical turbulence appears to be a critical factor: some vertical

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mixing is needed to maintain the supply of nutrients but too much turbulence prevents the phytoplankton from remaining sufficiently long in the euphotic zone to sustain growth. The right combination of physical properties is needed, and its appropriate formulation is an essential feature of models of biological production. Dr Tett described such a model, having the virtues of simplicity and of requiring the minimum of disposable parameters. It is a one-dimensional model which complements the one-dimensional physical model of the formation of structural fronts, and is a first step towards a more sophisticated representation of the processes involved.

An example of increased vertical mixing in a localized area leading to enhanced primary production was described by Mr Dooley. The initially stratified water of the Fair Isle current becomes vertically mixed by strong tidal currents in the Orkneys–Shetlands Channel, thus bringing nutrients into the upper layer, and increased primary production occurs further downstream where the current turns south into the North Sea. Increased vertical mixing is a possible cause of the enhanced productivity in the cold water band over the Celtic Sea shelf break but, as mentioned above, alternative physical processes have been suggested.

Future work

In this final section I note some outstanding problems which have emerged in the course of this Discussion Meeting. The choice is subjective, to some extent, and other participants may wish to question the choice or bring forward further ideas.

(i) The effect of oceanic flow on conditions on the northwest European shelf requires further investigation. Is the North Atlantic Current, in the attenuated form in which it reaches this side of the Atlantic, strong enough to exert a significant influence? In particular, is there a surface gradient from south to north along the shelf edge to maintain the long-term drift to the north off the west coast of Ireland and Scotland and through the Irish Sea?

(ii) The nature of the band of cold water that occurs in summer over the Celtic Sea shelf break has not yet been adequately explained. Is it due to upwelling, increased vertical mixing or a surface divergence produced in some other way?

(iii) The seasonal variation of fronts on the northwest European shelf has not yet been fully described. A sharp salinity front has been observed in winter off the Norwegian coast but there appears to be little evidence of whether similar fronts occur elsewhere on the shelf or at the shelf break.

(iv) The formation of structural fronts appears to be fairly well understood, and studies of the development of a seasonal thermocline have thrown some light on the efficiency of wind and tidal mixing. More detailed studies of the evolution of the thermocline might lead to basic information on the feedback process by which the efficiency of mixing is reduced as stratification develops.

(v) The dynamics of fronts, their instability and the formation of eddies need further investigation. Some very impressive infrared photographs from satellites have been presented and no doubt this technique will continue to provide valuable data on the location, characteristics and development of fronts. Similar synoptic views of the chlorophyll *a* concentration are becoming available with the use of the Coastal Zone Colour Scanner.

(vi) Cross-frontal mixing is an important aspect of the study of fronts, and several processes by which it can take place have been identified. A pertinent question is: To what extent do fronts or

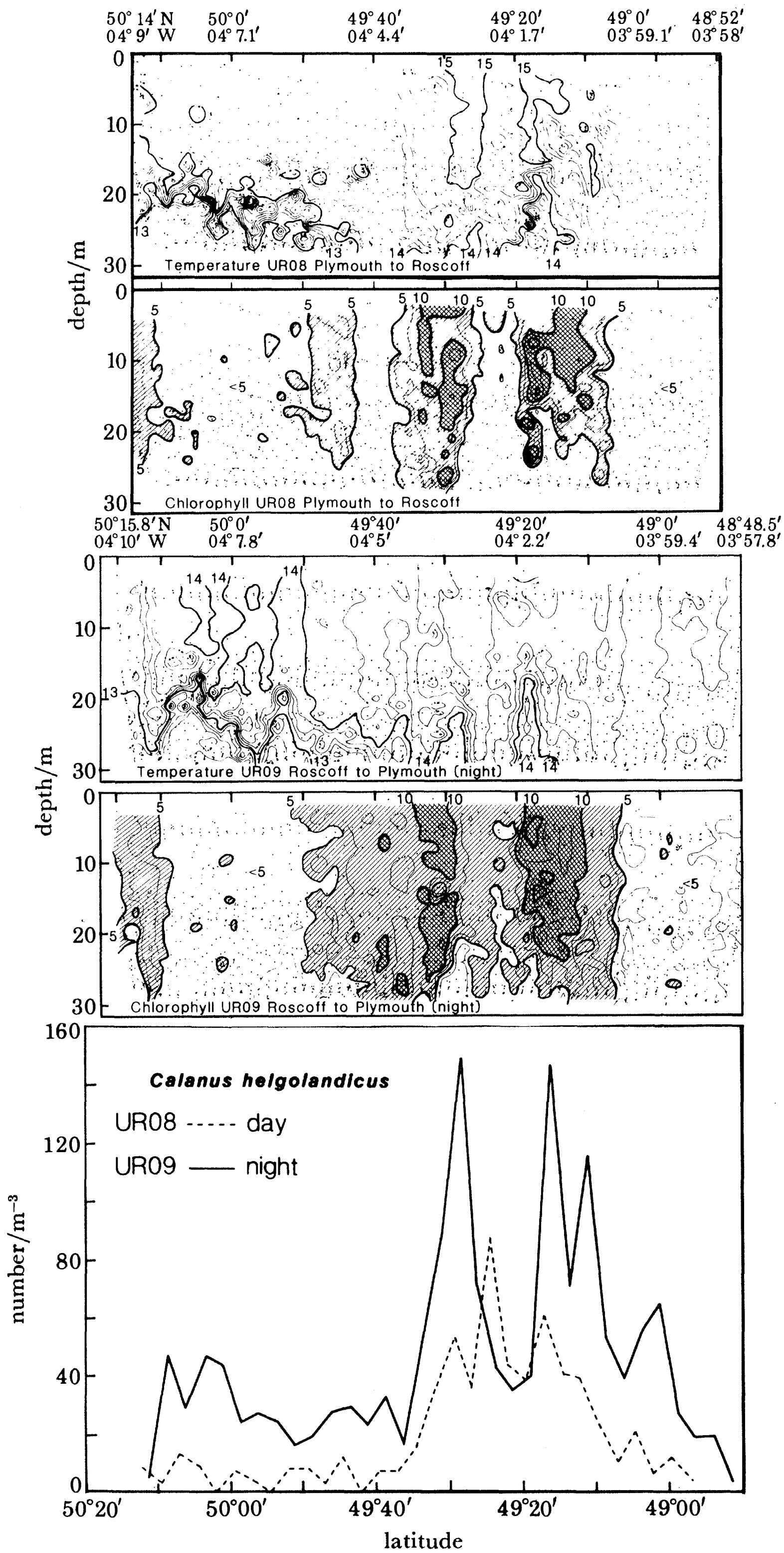

FIGURE 1. Vertical sections of temperature/°C and chlorophyll concentration/(mg m^{-3}), and the abundance of *Calanus helgolandicus* Claus recorded in the U.O.R. for successive day and night tows from Plymouth to Roscoff and Roscoff to Plymouth.

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coastally trapped currents restrict the mixing of coastal and oceanic water masses? This question is relevant to the use of coastal waters as a sink for sewage and industrial effluents, including radioactive wastes.

(vii) As a physical oceanographer, I hesitate to make suggestions on the biological aspects of circulation and fronts. One problem that seems self-evident, however, is to elucidate and quantify the role of the various physical factors that control the growth of phytoplankton in the vicinity of fronts.

Discussion

J. Aiken (*Institute for Marine Environmental Research, Prospect Place, The Hoe, Plymouth PL1 3DH, U.K.*). Mr Sinclair (Bedford Institute of Oceanography) has commented that some papers have tried to show relations at frontal systems between the first trophic level (phytoplankton/primary production) and the third trophic level (fish) but little or no work has been presented relating the first and second trophic levels (phytoplankton and zooplankton). The Undulating Oceanographic Recorder (U.O.R.) mark 2 is a self-contained sampler which can undulate to depths of 30 to 40 m when towed at high speed (up to 10 m s^{-1}). It carries a plankton sampler and instruments to measure salinity, temperature, chlorophyll concentration and radiant energy. Since April 1979, the U.O.R. mark 2 has been towed by the ferry M.V. *Cornouailles* from Plymouth to Roscoff in the western English Channel cutting across the frontal system that develops in this area in the summer and autumn; the instrument is launched and recovered by the crew of the vessel at full speed (*ca.* 9 m s^{-1}). Figure 1 shows the vertical sections of temperature/°C and chlorophyll concentration/(mg m^{-3}) with depth/m, and the abundance of *Calanus helgolandicus* Claus, the major herbivorous copepod in the plankton samples (4.5 km per sample), recorded in the U.O.R. for successive day and night tows from Plymouth to Roscoff and Roscoff to Plymouth in August 1979. The data show a strong thermocline at the northern end of the route, a double crossing of the frontal system (stratified, mixed, stratified) mid-channel, and a region of uniformly mixed water adjacent to the French coast at the southern end of the course. Highest concentrations of chlorophyll (up to 15 mg m^{-3}) and highest densities of *C. helgolandicus* (up to 150 m^{-3}) are observed in the stratified waters just inside the front.