Characteristics of an intense ocean frontal system in the upwell regime west of Cape Town

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ABSTRACT

During a week in February, 1968, a series of detailed BT transects of the frontal zone and out to 100 miles seawards demonstrated the location of the surface front between zones of inshore and offshore divergence, and between zones of surface mixing to seaward and bottom mixing beneath and inshore of the front. Marked changes in surface temperature patterns within hours of wind vector reversals emphasize the sensitivity of the wind stress/surface front intensity relationship but, due to more random variability, corresponding changes are not detectable at depth. The action of *mixing cells* within the front is shown to combine with overturning *events* to produce transient subthermoclinal sheets of relatively homogenous water. The cells also provide a postulated trans-frontal advection mechanism for small quanta.

1. Introduction

The area under discussion lies at the southern end of the oceanographically and economically important Benguela Current region. It has been scientifically investigated on many occasions, particularly by the S.A. Division of Sea Fisheries, using the traditional oceanographic method of reversing bottle sampling of the water column over a grid of rather widely spaced (10–25 miles)[1] stations. As a result it has been possible to locate and describe the various water masses found in the region, to account for the basic dynamic character of the Benguela system and to give some attention to the phenomenon of upwelling (Clowes, 1950; Hart & Currie, 1960; Shannon, 1966; Visser, 1969; Jones, 1971). More recently this Unit has embarked upon a supplementary programme in the same region aimed at a more detailed understanding of structural features such as thermoclines, fronts, upwell zones and divergence belts. Since important structural elements are often extremely localized and transient there has been a concomitant need for a finer and faster survey method. This need has been met by use of underway bathythermograph (BT) measurements whereby casts yielding continuous temperature/depth profiles down to 200 m are made at between 1 and 8 mile intervals along the lines covered. The system has obvious limitations, particularly due to the inherent imprecision of the BT (here estimated at ± 0.2°C), due to the fact that temperature is the only variable used, and due to the necessary confinement of measurements to the surface layer. Nevertheless when used in areas of strong gradients and in conjunction with earlier results the system has yielded satisfactory results, some of which are discussed below. The trend towards more intensive studies is also reflected in subsequent work by the Division of Sea Fisheries, where traditional methods have been complemented by airborne radiometer surveys to yield new information on processes within the upwell zone (Andrews & Cram, 1969; Andrews & Visser, in press).

Basic features of the environment are described in Fig. 1, constructed from continuous surface thermograph data obtained during a BT reconnaissance cruise in January, 1968, two weeks before the cruise described below. The water possessing a surface temperature of around 20°C has probably been derived mainly from the southern limb of the large scale South Atlantic gyre (not the West Wind Drift area which is several degrees cooler) and from a source of modified Agulhas Current water lying on the

[1] The unit *nautical mile* (1.85 km) is used throughout this discussion.

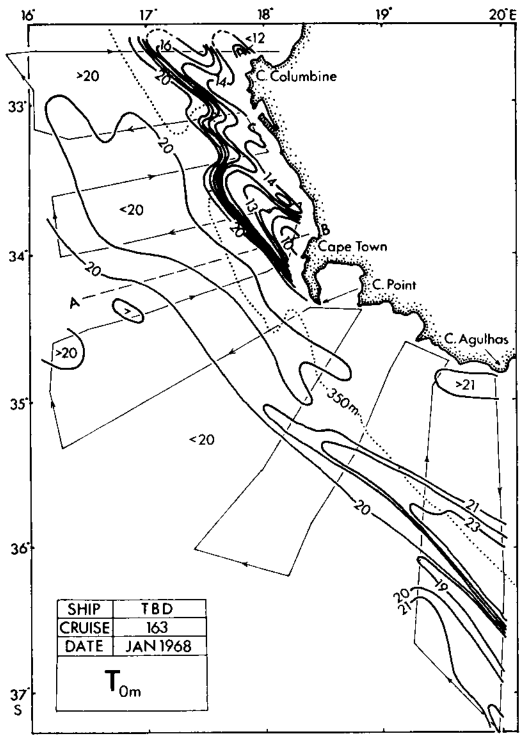

Fig. 1. Surface temperatures 20–28 January, 1968. derived from corrected surface thermograph records of R. V. Thomas B. Davie. Transect line of 5–10 February indicated AB. Notice upwelling inshore of strong frontal feature pivoted on Cape Point, and presence of Agulhas Current intrusion (23°C) in the south.

Agulhas Bank. Intruding into this fairly homogenous area from the south east is a shallow (50 m) tongue of virtually pure Agulhas Current water possessing a temperature of 22°C–23°C. West of the Cape Peninsula and along the coast northwards strong upwelling is in evidence, giving rise to temperature as low as 10°C. The overall impression is of a general north-northwestward surface set, particularly where tongues of upwelled water reach out from the main centres of upwelling off Cape Town and Cape Columbine.

The front forming the subject of this discussion is that region of strong surface temperature gradients separating upwelled water from oceanic water further offshore. Running northward from what might be termed a *pivot* (Bang, 1971) near Cape Point for at least 100 miles, the front possesses an overall temperature contrast of 8–10°C. Frontal gradients are comparable with those bounding the Gulf Stream or Kuroshio and considerably exceed those found in the upwell regimes of the American and North African west coasts.

During the period 5–10 February 1968, sixteen approximately normal transects of the front were completed, 10 of them based on the line AB, Fig. 1 and the remainder obtained between Cape Point and AB during a survey of the lateral extent of the front. Eight of the AB lines included BT observations.

Visual and radar fixes were possible out to 30–40 miles offshore but further out navigation depended on traditional astral methods.

In describing the front the rather unsatisfactory term "core region" has been used to denote the region of maximum surface temperature gradient lying between the 14° and 18°C isotherms.

2. Superficial character of the front

On all 16 intersections the front showd up as an abrupt step in the surface thermograph trace (Fig. 2), the frontal gradient being of the order of 1°C per mile. Occasionally, however, temperatures could be seen to change by several degrees within as many hundreds of metres. Although visual indications of the front were lacking on this occasion, it showed up clearly on the radar as a band of damped sea clutter and was frequently associated with an increased concentration of biological contacts on the bathymetric echo-sounder. Examining Fig. 2 the initial impression is of the similarity between outward and return transects. Closer examination shows, however, that the trace character varies considerably with time and that cooler patches to seaward of the front (e.g. features *b* and *d*, Fig. 2) appear and disappear with great rapidity. These are associated with activity in the offshore divergence/disturbance zone discussed later.

Lowest temperatures are found immediately adjacent to the front, temperatures in Table Bay being substantially higher and more variable. The inshore situation agrees closely with the results of Andrews and Cram (1968) and Andrews and Visser (in press) which show that surface temperatures lower than 10°C can usually be taken to represent active upwelling and

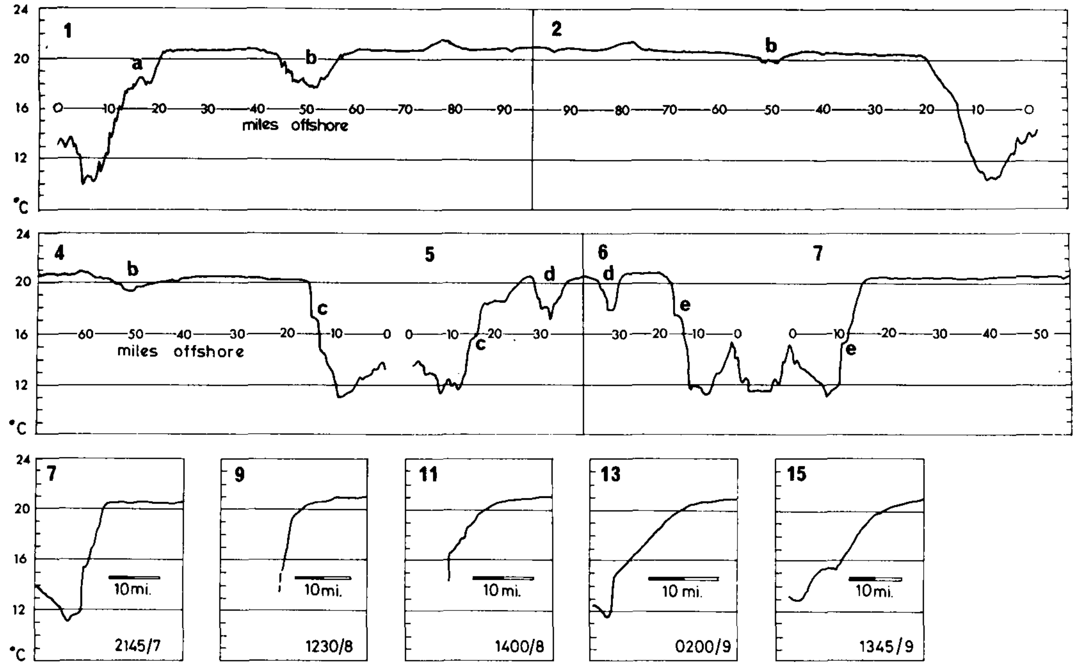

Fig. 2. Frontal transect surface thermograph records 5–10 February, 1968. Horizontal scale given (approx.) in terms of distance. Transect numbers indicated *1–15*; thermal features discussed in text denoted *a–e*.

that this activity is often centered on the locality indicated in Fig. 1.

Small steps in the thermograph trace such as those denoted *a*, *c*, *e*, Fig. 2 are characteristic of all the AB transects. Close examination of these, particularly *e*, indicates a possible tendency towards eastward migration with a concurrent fall in temperature. BT data show that the steps are manifestations of shallow pockets or *cells* of mixing imbedded within the front. Progressive entrainment of cooler water as the cells move across the front explains the fall in temperature. Initially the movement of a warm cell towards the core of the front must be construed as a factor favouring frontal intensification—a situation analogous to the downward migration of storm-generated thermocline steps and the resultant intensification of the seasonal thermocline. However, continued penetration of mixing cells may split the front into two or more lesser fronts (e.g. transect **15**, Fig. 2) and, ultimately, passage of a small quantum of heat right across the frontal zone will result in an elementary dimunition of the overall frontal gradient. The contribution of these cells to frontal processes is discussed further under Bathythermography below.

3. Time variations in surface temperature

Although surface temperature is commonly regarded as a rather fickle parameter, a comprehensive series of airborne radiometer studies with shipborne reference measurements has shown that it is a valuable indicator of local oceanic processes (Andrews & Cram, 1969). This fact, together with the increasing use of satellite data and surface temperature charts such as the 10-day charts issued by the S.A. Maritime Weather Office (Crawford, 1970) make it useful to consider the behaviour of surface temperatures in the vicinity of a frontal zone during an atmospheric cycle.

The first part of the survey was carried out under the moderate southerly wind conditions characteristically associated with wind-stress upwelling, conditions which had been prevalent through much of the preceeding month. At about 0100/8.2.1968, however, the wind veered

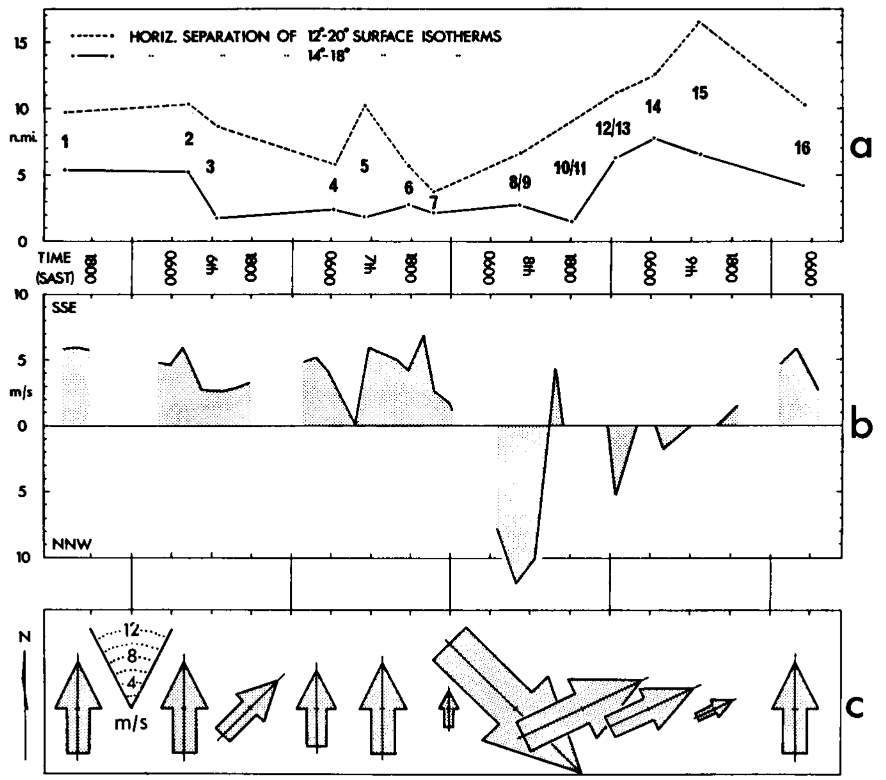

Fig. 3. Front intensity (*a*), resolved wind component (*b*), and wind vector (*c*) interrelationships. Positive components are theoretically favourable to upwelling.

rapidly and freshened, eventually reaching a full northwesterly gale for several hours, and then backed to the south once more, shortly before commencement of the last transect. Opportunities to study the oceanic effects of such a cycle are rare. Consequently, in order to make the best of the limited data available, two assumptions have been made. Firstly, in the absence of a closer fixed recording station, the wind vectors used are those recorded by the ship itself while within 25 miles of the front. Secondly, transects 8 to **13**, which were obtained at various distances south of the standard line during a survey towards Cape Point, have been used in the construction of Fig. 3. Wind velocities and concurrent adjustments in frontal intensity (as indicated by horizontal separation of surface isotherms) are recorded in Fig. 3. The boldness of the vector arrows—proportional to v^2—gives a rough indication of the magnitude of the wind stress exerted on the sea surface.[1] Corresponding to the four distinct weather phases indicated by the wind velocities, one finds the front intensifying under southerly conditions, then weakening rapidly with the onset of the gale and ensuing southwesterly conditions and, finally, intensifying again as the wind backs round to the south once more. The cycle of frontal adjustment is more clearly illustrated in Fig. 2 where transects **1** to **7** show a progressively sharper, and **7** to **13** a progressively weaker, discontinuity. More significant than these broad trends are the following:

(i) the rapidity with which the front, particularly its fringes, responds to changes in wind-stress. As examples, the horizontal distance between the 12 and 20°C isotherms increases from the 3.7 to 6.6 miles within something less

[1] See Roll (1965), pp. 152–167, for an evaluation of the many quantitative estimates of this force, most of which involve the square of the mean wind speed at some fixed height.

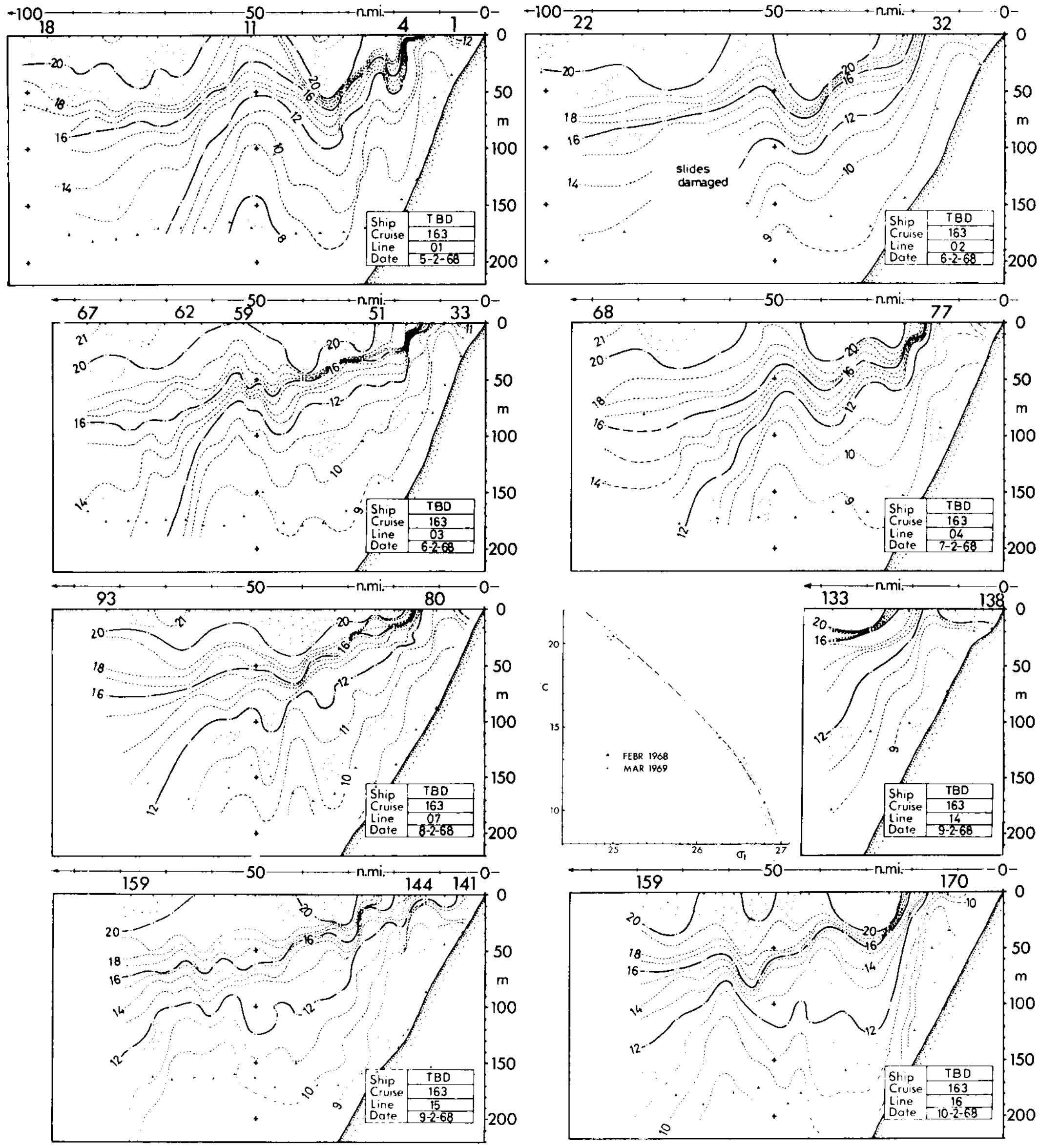

Fig. 4. Eight BT sections obtained along line AB, Fig. 1, over a period of 5 days. Left hand column is based on dips at 1/2 hourly (4–5 mile) intervals; right hand column on hourly (8–10 mile) dips. Shaded areas are isothermal. Individual dips mentioned in text are identified by the numbers along the top of each section. Inset gives an idea of the temperature/density correlation in the section in consecutive years.

than 12 hours during the transition period between southerly and north-westerly phases, and decreases from 16.5 to 10.2 miles in 16 hours as the final south-easterly phase commences.

(ii) the behaviour of the core of the front (solid line, Fig. 3*a*). Reaching an apparent equilibrium intensity of about 2°C per mile by 1 300/6th, this gradient is maintained until somewhat after the gale had abated, when a very rapid weakening took place. Transect **13**, Fig. 2, shows that although the seaward fringe of the front had by then been drastically effected, a strong core gradient persisted until at least 0200/9th. A second feature is the fact that the core gradient thereafter began to intensity many hours *before* onset of the final south-easterly phase, this intensification taking place despite continued surface mixing resulting from the persistence of the stormgenerated sea state. It is thus apparent that the core gradient is predominantly a function of some factor other than short-term wind-stress or surface mixing.

4. Bathythermography

Based on the temperature/density correlation inset in Fig. 4 and on extensive local experience one may make the initial assumption that temperature is a good indicator of density in this region, at least within the limits of accuracy of the BT system, and that the thermocline corresponds to the pycnocline, the thermal front to a density discontinuity and that the inclination of the front as determined from the dip of isothermal surfaces is equivalent to that which would be obtained from density measurements. This correlation does not invariably extend into the micro-scale, however, where there is occasional evidence of salinity compensation in thermal inversions such that the resultant structure is stable (Visser, personal communication). In this context, therefore, some of the ubiquitous thermal inversions encountered in the frontal zone may, in fact, represent conditions of neutral or slightly positive stability.

Examining the sections of Fig. 4 the initial impression is one of rather chaotic variability. It is, however, possible to isolate a number of structural elements which may be examined individually and then integrated into a reasonably coherent two-dimensional model. Systematic projection of this model into the time dimension is largely inhibited by the rather peculiar time/space distribution of observations in this sort of survey and by the potentially important effects of imperfect navigation and advection. In particular the resolution obtainable is such as to preclude any systematic examination of possible structural adjustments to the "switching off" and "switching on" of the upwell inducing wind stress due to the northerly gale. In fact the sections and traces yield no consistent evidence of mixed layer deepening or of thermocline sharpening and it is clear that, despite the obvious surface agitation, mixing was confined to a surface layer no more than 10 m or so in thickness.

The inshore frontal zone, formed by the outcropping of the seasonal thermocline 10–15 miles offshore, is dominated by the activity of the *mixing cells* alluded to above. Possessing depths of 5–20 m, widths of 2–5 miles and a rate of shoreward progression (very roughly estimated from the surface thermograph record) of something under half a knot, these enigmatic features have a dimensional resemblance to an order of internal waves encountered during other projects in this area.[1] One may thus postulate the generation of internal waves in the divergence/disturbance belt and their progression up the thermocline plane towards the coast. The physical modification of such waves as they approach the surface outcrop of a discontinuity has not, to the author's knowledge, been treated theoretically but the present suggestion that they shake themselves out in the form of mixing cells appears to have observational validity.

Separated from the inshore frontal system by a trough of well-mixed oceanic water, the *offshore upwell region* is the most significant feature of the offshore structure. It closely resembles the analogous structure described further north (Bang, 1971), though transect **1** appears to illustrate a more active situation than has hitherto been intersected. Despite its virtual disappearance in transects **7** and **15**, transect **16** provides evidence of renewed sub-surface ridging and a trend towards restoration of a type situation similar to transect **1**. The strong subsurface gradients forming the seaward boundary of the divergence constitute another frontal system. This, because of its much greater depth extent (see the data presented by Shannon (1966) for instance), is a dynamically more important feature than the inshore front but is more properly the subject of study on a larger scale than the present meso-scale investigation. It is nevertheless clear that a belt of enhanced northward current velocity should be expected 60–80 miles offshore, a deduction supported by the strong northward set (greater than 1 knot) experienced during the offshore stages of tran-

[1] One and two ship anchor stations and echo-sounder records of scattering layer configurations.

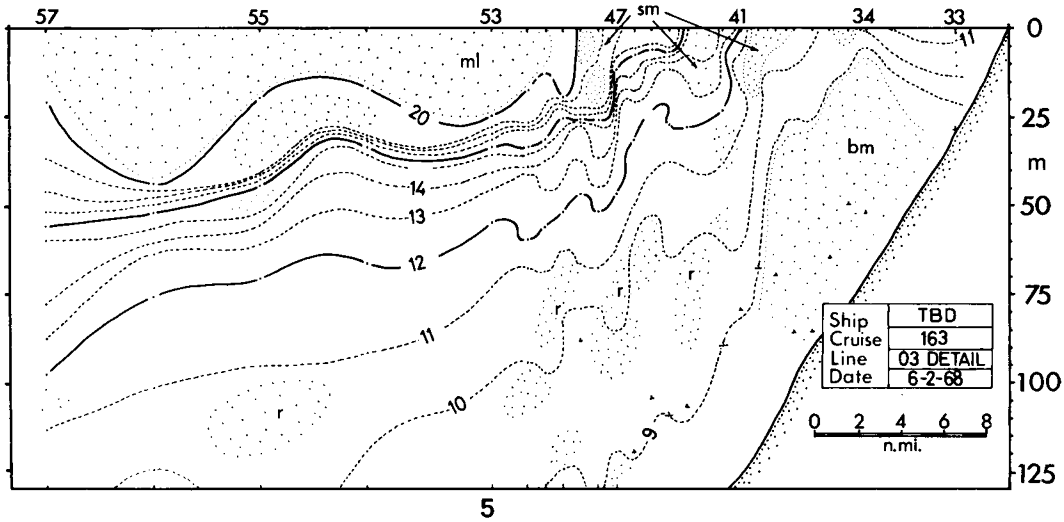

Fig. 5. Detailed section through front. Annotation *bm* indicates bottom mixed layer, *sm* the surface mixing cells, *ml* the normal offshore mixed layer and *r* relic pockets or sheets of isothermal water attributed to previous overturning events.

sects 1 and 2 and by micro-structural features characteristic of shear/disturbance conditions on the seaward flank of the divergence (see Fig. 6*b*).

Due to the lack of an observational foundation no generally acceptable explanation of the offshore divergence has yet appeared. It is, for instance, impossible to state (a) whether it consists of a linear divergence streak as demanded by the model of Hart and Currie (1960) and by any steady state explanation, (b) whether it is the consequence of a procession of cyclonic eddies generated intermittantly in the shoreward shear zone of an equatorward jet over the continental slope (Bang, 1972) or (c) whether it is the result of large-scale internal breakers and consequent vertical mixing in that vicinity (Tomczak, 1973). Circumstantial evidence against the last possibility, however, is the depth of water in which the divergence is here located (1 000 m) and the absence of mixing indications during exposure of cold water (transect 1), while the obvious intermittancy of the process weakens the case for steady-state explanations. In any case, however, the shelf-edge situation may be visualized as the first stage of a two stage "pump" whereby Central water (as defined by Shannon, 1966) is dynamically elevated to the 100–200 m level or shallower. At this point the second stage takes over as water is drawn upwards and shorewards by the local wind stress/Ekman transport mechanism.

The location of an *isothermal lens* immediately beneath and inshore of the surface front is indicative of bottom turbulence, the layer being bounded above by a sharp inverted thermocline nick point (see traces 33–39, Fig. 6*a*). It corresponds to a similar mixed layer discovered subsequently off the Oregon coast, and its position in section corresponds to that of the inshore poleward counter current observed in that region by Mooers, Collins and Smith (1972) and reproduced numerically by McNider & O'Brien (1972). It also appears to form part of the *shelf water* described by Andrews & Visser (in press) which lies on the bottom and is normally somewhat isolated from the upwell circulation. One possible explanation, that of bottom mixing by the sub-surface countercurrent, has not been expressly put forward in the American literature, probably because of the difficulty of treating bottom friction and mixing in model studies. In addition, the position and character of the bottom lens must be expected to adjust continuously to changes in surface wind stress, being drawn upward as the upwell circulation intensifies and falling back as it weakens. Intermittent adjustments of this sort must inevitably result in frictional mixing in the bottom layer, particularly in this area of

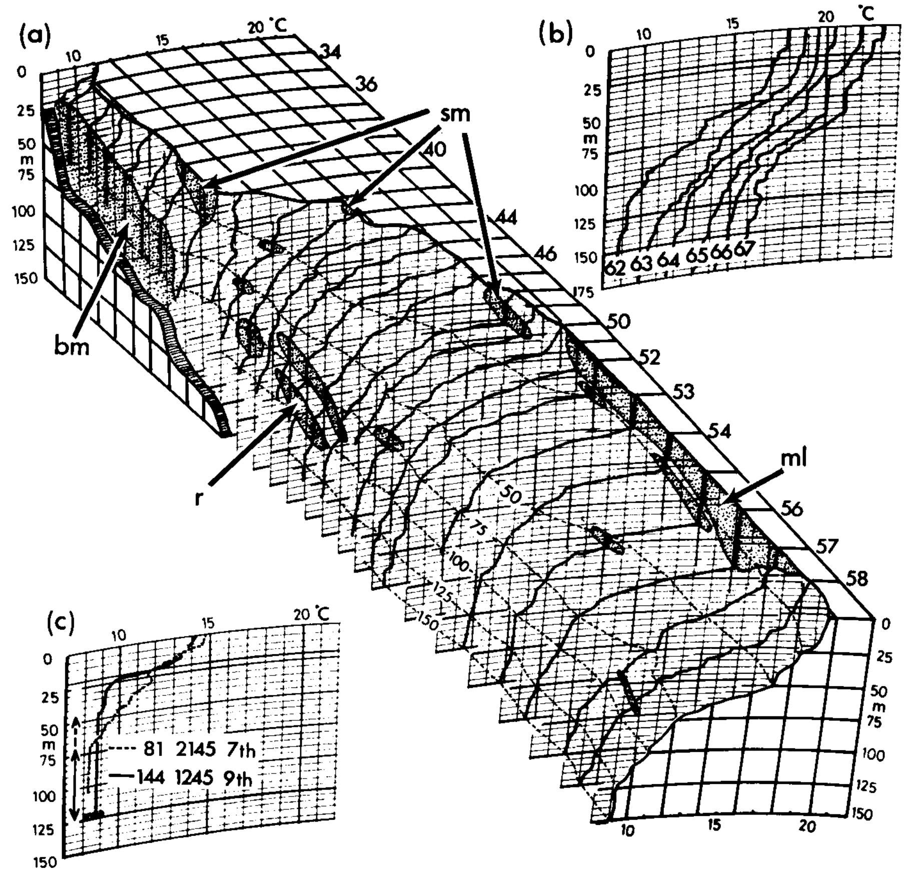

Fig. 6. (*a*) superimposition of the 26 traces which yielded Fig. 5 to show coherence and extent of isothermal regions in relation to trace morphology. See Fig. 5 for annotations and text for further interpretation. (*b*) offset BT traces obtained to seaward of divergence, with erratic structure suggestive of shear/disturbance conditions. Trace 65 is correct, others are displaced progressively by 1°C. (*c*) deepening and warming of bottom mixed layer, probably due to enhanced mixing during intervening period of wind fluctuations. Positions of dips shown in Fig. 4.

broken bottom topography. Comparison of transect **15** with previous sections shows that the mixed layer has become more extensive and more clearly defined during the intervening period of wind reversals (see Fig. 6*c*).

5. Frontal mixing and transfrontal advection

The detailed portion of transect **3** (Fig. 5) was generated by a rapid sequence of BT dips spaced at approximately one mile intervals. The sandwiching of the frontal region between zones of offshore surface mixing and inshore bottom mixing is evident. A study of the several mixing cells imbedded in the front enables one to outline a further, *intra-frontal*, mixing process whereby upwelled water moving seawards is temporarily forced into unstable vertical juxtaposition with somewhat warmer frontal water (trace 41, Fig. 6). Intermittent collapse of this situation will produce sinking and mixing and the entrainment of water from the adjacent decaying mixing cell. The resultant mixture thus possesses, in this case, a temperature of 10–11°C and will tend to slip back parallel to these isotherms. A study of the other sections of Fig. 4 suggests that although there is persistent evidence of instability and mixing on the shoreward fringe of the front there is little evidence of the formation of a consistent sub-thermoclinal water mass. The indications are rather that each collapsing and mixing *event* produces a pocket or sheet of mixed water of slightly differing hydrological character, depending on the degree of initial instability and on the amount of frontal water subsequently entrained. Subthermoclinal *relics* of previous overturning events in the form of mixed layers of varying temperature and varying lateral extent are thus to be found in all sections obtained. Sheets possessing characteristics differing only slightly from the upwelling mass are likely, in turn, to be entrained in that circulation, but the products of more violent mixing events, having entrained a greater proportion of frontal water, will tend to lodge immediately beneath the thermocline until diffused by the effects of internal wave and other disturbances.

Fig. 6*a* presents the data in a somewhat complex but more comprehensive form. It was obtained by offset superimposition of the actual BT cards, suitably trimmed, and thus gives

(i) 26 BT traces each of which may be read individually without undue difficulty,[1]

(ii) a representation of the surface thermograph record (upper surface of block) and

(iii) a much better idea of the coherence and extent of isothermal regions.

The inclination of these sheets is shown by comparison with dashed equal depth "contours". Conditions of suspect stability are illustrated in traces 36, 37 and 41, the inversion in trace 44 having the position and appearance of a salinity compensated, stable inversion occasionally found at the base of a strong thermocline. Erratic structure on the shoreward flank of the divergence is shown in traces 57 and 58.

One problem of the present investigation was to reconcile periodic evidence of frontal breakthroughs (e.g. bathers' reports of *physalia physalia*, an Agulhas fauna) with oceanographic evidence from a number of surveys and merchant ship observations that the front had maintained its integrity throughout the months of January and February. The mixing cell concept provides a solution. Although mixing will have brought its temperature down to very near that of the upwelled water during the transfrontal migration process, the cell will retain much of its biological content, particularly of the larger buoyant animals. These biological quanta will eventually be discharged into the upwell region, where varying eddies and counter currents will distribute their contents, occasionally onto the beaches. The mixing cell mechanism may thus be visualized as a sort of "air-lock" whereby transfrontal transport of small quanta is effected without complete rupture of the front occurring at any time.

[1] A transparency may be made from Fig. 6c and appropriately superimposed.

6. Conclusion

The recent resurgence of upwell studies has provided and is providing a body of new information and ideas which impinge directly on Benguela research. Nevertheless it is clear from comparison of the preliminary results and conclusions relating to the work off Oregon (C.U.E. Notes, 1972) with those obtained off North West Africa (Jones, 1972; Tomczak, 1972) that recent research has probably generated more questions than answers and that the immediate need is for much more observational material, particularly from an area where upwell processes and characteristics appear to be more sharply defined than is the case off Oregon, the Sahara or Peru. The present discussion is thus aimed at providing additional observational illumination, and at the definition of conceptual elements such as the frontal mixing cell. The next step, planned for early 1973, is to further exploit Cape Town's doorstep upwell laboratory using a new generation of equipment including current meters, STD profiles and an accurate navigation system, none of which has hitherto been available to unfortunate local scientists. This should generate the relative small quantity of data required to project the present descriptive model into the realm of quantitative study, and will pave the way for a more comprehensive treatise on the relationship between the present work and the spate of important upwell and finescale fluid behaviour studies which have recently appeared or are still in the press.

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ХАРАКТЕРИСТИКИ ИНТЕНСИВНОЙ ФРОНТАЛЬНОЙ СИСТЕМЫ В ОКЕАНЕ В РЕЖИМЕ ПОДНЯТИЯ ВОД К ЗАПАДУ ОТ КЭЙПТАУНА

Серия детальных разрезов фронтальной зоны и областей до 100 миль в направлении открытого моря, проведенных в течение недели февраля 1968 г., выявила положение фронта на поверхности между зонами дивергенции к берегу и от берега и между зонами смещения на поверхности в направлении к морю и приданного смещения к берегу от фронта и под ним. Заметные изменения в поле температур на поверхности за время в несколько часов после изменений направления ветра подчеркивают чувствительность соотношения между напряжением ветра и интенсивностью фронта, но, благодаря случайной изменчивости ветра, соответствующие изменения не ощущаются на глубине. Показано, что действие ячеек смещения внутри фронта комбинируется с событиями перевертывания масс, в результате чего образуются переходные субтермоклинальные слои относительно однородных водных масс. Ячейки также обеспечивают постулируемый механизм адвекции небольших количеств жидкости через фронт раздела.