Direct current measurements of a shelf-edge frontal jet in the southern Benguela system[1]

N. D. Bang[2]

C.S.I.R. Oceanographic Research Unit,
University of Cape Town,
Rondebosch, R.S.A.

W. R. H. Andrews

Sea Fisheries Branch,
Department of Industries,
Sea Point, R.S.A.

ABSTRACT

A bathythermograph section generated during the outward run along a 100 mile line running 255° from Cape Town was used to condition the positioning of a series of direct current measurements during the inward run along the same line. The latter produced the first direct measurement current velocity section across the Benguela system. As predicted from ealier thermal structure research, a strongly baroclinic frontal zone near the shelf-break was shown to contain an intense equatorward jet of maximum velocity 1.2 m/sec. and a volume transport of about $7 \times 10^6 \, m^3/sec$. The position and character of the jet are related both to the internal redistribution of mass in the eastern boundary zone of the wind-driven South Atlantic gyre and to the more localised system of coastal upwelling. Its theoretically unexpected intensity is provisionally attributed to the particular form of the local horizontal wind profile.

1. Introduction

Since 1966 physical research in the Oceanographic Research Unit at the University of Cape Town has been directed towards the isolation and description of elements of the oceanic structure and circulation which occur on smaller time and distance scales than were accessible to traditional oceanographic methods used previously. Through systematic exploitation of the many practical attributes of the bathythermograph (BT) considerable progress has been made towards projecting earlier, steady-state, "climatic" idealisations towards a more "synoptic" and dynamic understanding based mainly on frontal concepts (Bang, 1971; 1973b).

1. Received: *10 October 1973*; revised: *28 March 1974*.
2. Present address: Geophysical Institute, University of Bergen, Norway.

More recently the needs of modern fisheries hydrography emphasized by an apparent decline in Benguela pilchard stocks have been met by a realignment of the research policies of the Sea Fisheries Branch of the S.A. Department of Industries. The pattern of extended routine hydrological sampling, having provided a solid, macro-scale foundation (see Shannon, 1966), has been replaced by more intensive inshore studies. In this case standard, though closely spaced, reversing bottle observations were supplemented by repeated airborne radiometer (ART) surveys of the research region. Some of these results have been reported in Andrews and Cram (1969), Cram (1973) and Andrews (1974).

The two programmes are essentially complementary; the Sea Fisheries Branch being interested mainly in the biology and biochemistry of the upwelled mass, while the Unit is more particularly concerned with the mesoscale dynamic structure to seaward.

The present opportunity arose when within a relatively short space of time the local oceanographic outlook was revolutionised by the installation of a Decca Navigator chain, by the acquisition by the Branch of a Plessey current meter, a Bissett-Berman Salinity/Temperature/Depth/Oxygen (STDO) system, and a Thermosalinograph (T-SG). This combination of circumstances obviously provided an opportunity of linking the thermal inferences of previous BT and on-going ART programmes to actual velocity and fine-scale density measurements and thus of confirming (or discounting) the validity of the underlying thermal inference premises. In a sense the short programme which resulted was premature in that the STDO was still possessed by several electronic devils, while no proper current meter winch had yet been fitted to R.V. BENGUELA. Nevertheless in view of the undesireability of carrying out the project under conditions of weaker structure later in the year it was decided to proceed as planned.

2. Instrumentation

The STDO (B-B Model 9040) incorporated sophisticated graphic, digital read-out and digital logging laboratory modules. Temperature and oxygen components worked perfectly but salinity spiking caused concern despite the very slow descent rates employed. Also an untraced fault in the system's depth drive circuitry made it impossible to place more than a rough depth scale on the profiles obtained. These problems, which will probably be remedied as more practical and electronic experience is obtained, made it necessary to fall back on the conventional BT for basic thermal coverage.

The current meter (Plessey Type MO27) was of the propellor type with portable deck read-out speed and direction modules. Although designed for lowering on co-axial cable from its own winch, absence of the latter facility necessitated lowering of the meter on the hydrographic wire while simultaneously paying out the meter cable from a hand-wound reel on deck. The difficulties and hazards of this operation will be appreciated but thanks to very

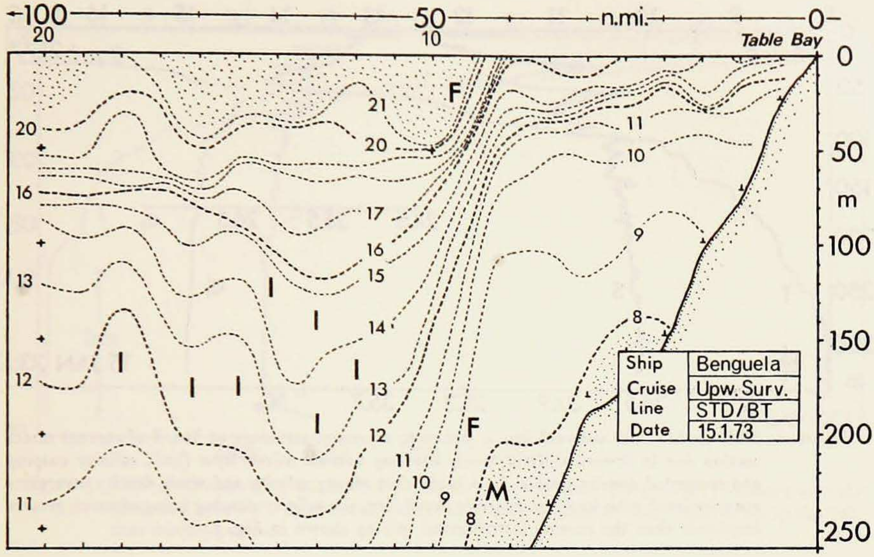

Figure 1. BT section running 255° from Cape Town, 15–16 January, 1973. Note the intensity of the offshore front (FF), the configuration of the 10° and 11° isotherms indicating a 200 m + step within the frontal zone. Note also the numerous sub-thermoclinal inversions (I) west of the front, the bottom mixed layer (M), and that coastal upwelling is not occurring.

favourable weather and sea conditions no serious foul-ups occurred. At each depth five observations of speed and direction were normally obtained: if these were badly scattered, additional observations were made until a grouping pattern became apparent. The measured vector was then ascertained by inspection. True current vectors were later obtained by eliminating the ship drift vector as deduced by Decca fixes. No instrumental problems were encountered.

The Barnes PRT 5 radiation thermometer incorporated graphic and digital outputs and a digital logger. While the ship was at sea calibration runs along the ship's track (marked by a succession of dye patches) were made each day. The instrument has flown many hundreds of hours in previous and subsequent surveys and is obviously well suited to the Benguela environment and to present research requirements.

3. Measurement programme

The programme consisted of several elements:

(i) Eleven consecutive days of ART flying (14–24 Jan. 1973), the grid shown in Fig. 5 being flown every day, an eight or nine hour flight.

(ii) A 100 mile line of STDO and BT stations at 5 mile intervals (See Fig. 5). commencing in Table Bay at 1000 on the 15th and concluding at 0300

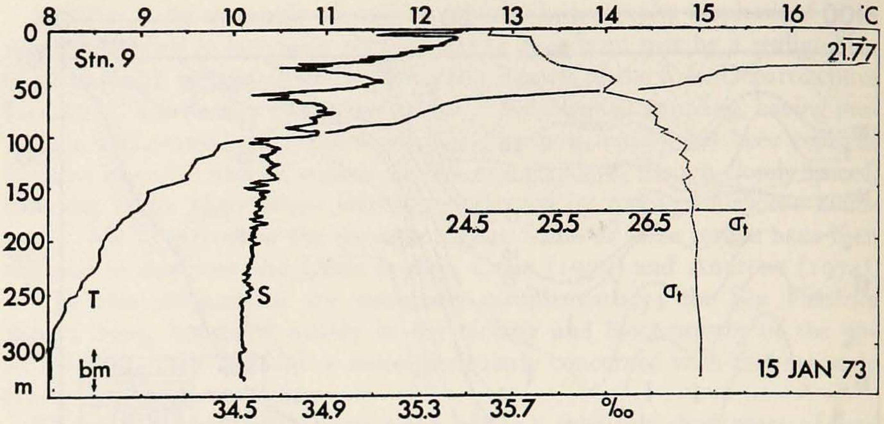

Figure 2. STD profile from outward Stn. 9 (taken to represent structure at Stn. 8 of current meter section due to inward shift of front) showing bottom mixed layer (bm), salinity cusping and computed density profile. It is likely that strong salinity and weak density inversions are associated with localised dynamic instability, the salinity cusping being of much greater amplitude than the normal instrumental spiking shown in Fig. 3.

on the 16th. A BT section (Fig. 1) was plotted as the stations were completed.

(iii) A series of 8 current meter stations on the inward leg of the same line, occupied between 0630 and 2100 on the 16th, the first station being occupied well after the period of suspect Decca behaviour around sunrise.

(iv) The routine monthly upwell plume sampling programme (17th and 18th Jan.), this work forming part of a longer-term project to be reported on elsewhere (Andrews and Visser, 1974).

4. Results

a. *Thermal structure.* From the BT section of Fig. 1 it is clear that inshore upwelling was not taking place at the time, surface temperature inshore being well above the 10°C value normally taken to indicate active upwelling. This isotherm in fact lay at a depth of at least 30 m. On the other hand there is little sign of downwelling. An elementary order of magnitude calculation shows that the warm surface layer cannot be attributed to solar heating over a few days of oceanic inactivity. Warm oceanic water has clearly leaked into the upwell cell.

Stations 5 to 8 yielded indications of the bottom mixed layer (see Figs. 2 and 3) discussed in Bang (1973b), though its definition is poorer and it is located at a somewhat greater depth. The relatively high surface layer temperatures in the off-shore region suggest that this oceanic water is of Agulhas origin.

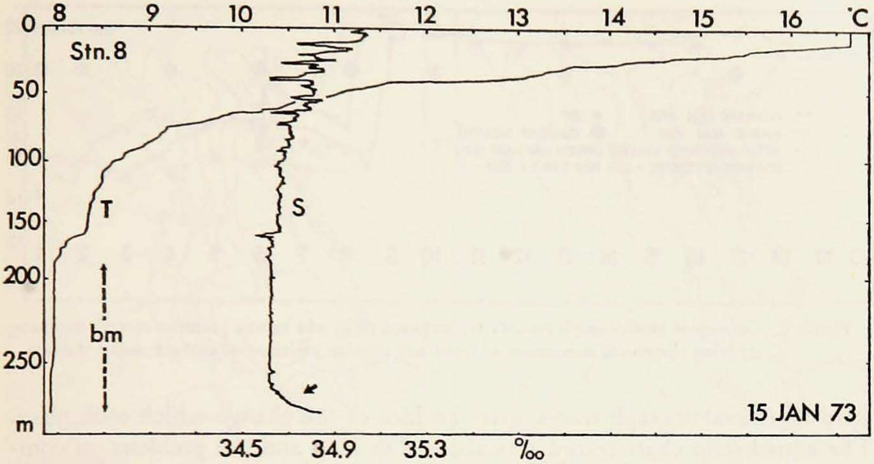

Figure 3. STD profile showing homogeneity of bottom mixed layer. Sharp salinity increase near the bottom is possibly a conductivity effect of a dense nephritic "soup" stirred up by the bottom mixing process.

b. *Postulated dynamic structure.* Drawing the dynamic inference from Fig. 1 it was expected that the very strong front here demarcated would be associated with a strong equatorward jet, the axis of maximum surface current velocity lying in the vicinity of Stn. 10. Secondly, the broad trough between Stns. 9 and 18 is suggestive of an anticyclonic couple centred on Stn. 13. However due to the possible effects of differing mass distributions in the layers beneath the observed section, such an interpretation would be put forward with caution. There are no structural indications of similar couples east of the front.

These were the considerations in mind as the ship was put about to start current measurements in the same section. In view of the poor Decca cuts available at this range and the low current velocities expected, it was planned to occupy Station 17 more as a procedural exercise than as a serious attempt to obtain current measurements. It was hoped that measurements at Station 13 would give an indication of the velocity of the S.E. Trade Wind Drift, while Stations 8 and 10 were selected as providing possibilities for quantifying Margules equation in relation to thermal data. The interest in inshore measurements lay mainly in trying to relate the bottom mixed layer to the poleward counter-current of theoretical models.

The difficulties encountered in manhandling the current meter cable at Station 17 and the need to meet a fairly rigorous time schedule made it impossible to carry out concurrent STDO measurements on the inward leg.

c. *Changes in position of frontal axis between outward thermal structure and inward velocity structure observations.* Fig. 4, constructed from outward and in-

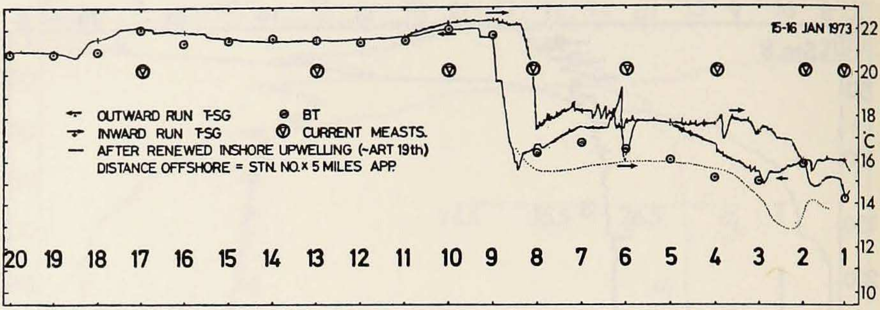

Figure 4. Condensed thermograph records for outward (BT) and return (current meter) transects, showing shoreward movement of front and relative positions of current meter stations.

ward thermosalinograph traces, gives an idea of the change which took place. The actual strip chart record was about 8 m long and the problems of compressing this laterally to produce a reproduceable diagram will be appreciated. The diagram thus gives only a very rough impression of the trace character between point measurements at the stations. Nevertheless it is clear that the front moved 3–4 miles shorewards during the 20 hour interval.

The ART charts (Figs. 5 and 6) suggest an even greater shift. The apparent movement (miles shorewards) of isotherms may be tabulated as follows:–

Isotherm............	21	20	19	18	17	16	°C
ART...............	–	7	15	17	17	17	miles
T-SG.............	3	4	4	3	–	–	miles

The interpretation here is that the front itself moved no more than 4 miles shorewards but that in the surface layer between the 2 m depth of the surface thermograph sensor and the surface film sensed by the ART, the front lost its integrity and a layer of warm oceanic surface water a metre or so in depth was blown over the top of the front into the upwell cell.

d. *Observed velocity structure.* Isotachs of velocity resolved normal to the transect line are shown in Fig. 7, positive values indicating equatorward movement. The superimposed 13°C isotherm is that of Fig. 1 moved one station interval shorewards. Although the presence of a jet had been expected, it must be admitted that its emergence thus from the digital current measurement data was greeted with oceanographic emotions analogous to Carter's archaeological feelings during the final rubble clearing in the Valley of the Kings in November, 1922!

The direction of the jet was very nearly at right angles to the transect and parallel to the frontal isotherms of Figs. 5 and 6. Our experience is that with such a clearly defined feature the surface isotherms give a good indication of

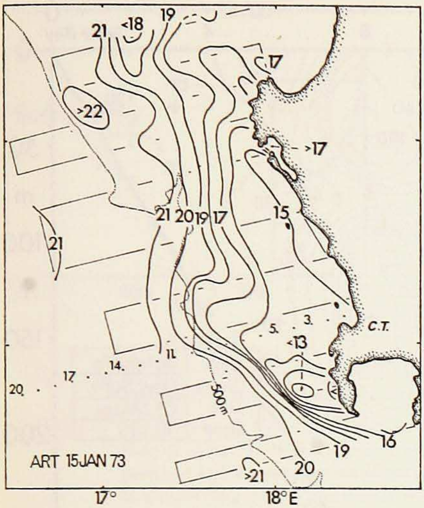

Figure 5.

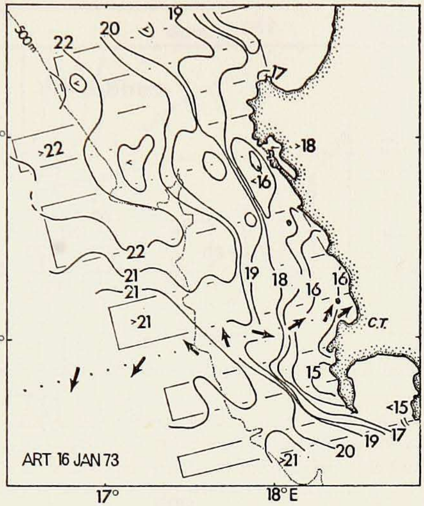

Figure 6.

Figure 5 (left). ART chart coinciding with outward BT transect. Note the front bounding expanded but temporarily quiescent Cape upwell cell. BT stations shown. Wind conditions—strong southerly previous day becoming light south-westerly during night.

Figure 6. ART chart coinciding with current meter transect. Note apparent weakening of front in line of transect as film of oceanic water spreads shorewards, and general disorganisation of isotherms. Wind conditions—light westerly. Arrows indicate direction of current vectors at 25 m.

the trend of isotherms or isopycnals at any deeper level within the oceanic troposphere and we conclude therefore that the jet is geostrophically orientated with respect to deeper density gradients constituting the front. This deduction applies specifically to the jet/front relationship, not to conditions inshore where temperature/density/velocity relationships appear to be much more complex due to weak gradients, transient states and bottom friction.

The direction of vectors at various depths at each station was unsystematically scattered within a small arc of about 40° or less.

A volume transport estimate based on the areas enclosed by the various isotachs yielded on estimate of $5.1 \times 10^6 m^3/sec$ for the region above 200 m: a total jet transport of about $7 \times 10^6 m^3/sec$ may thus be suggested.

West of the jet a strong anticyclonic circulation is demarcated, indicating that jet transport may be locally compensated by large scale eddying to seaward. Such a contention rests heavily on some poorly conditioned navigational fixes at Stns 17 and 13 and will certainly require verification. Inshore there are indications both of a small, shallow cyclonic couple and of a deeper poleward component, probably related to the poleward under-current of De Decker (1970) and of other upwell regions. This component does, in fact, appear to be associated with the bottom mixed layer of Fig. 1 and of Bang (1973b).

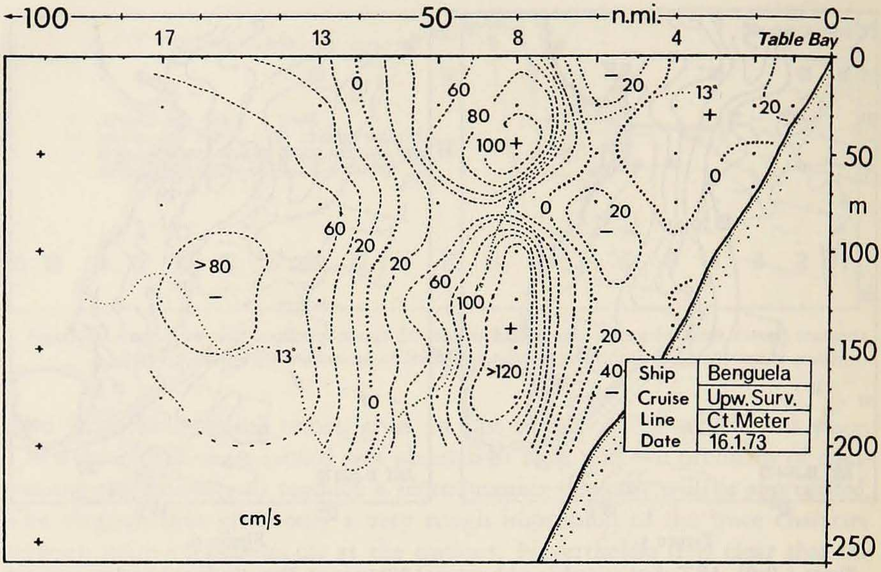

Figure 7. Isotachs of velocity (cm/sec.) resolved normal to transect line. Frontal jet shows up prominantly, apparently bisected by thermocline. Southward components (neg.) indicate presence of anticyclonic circulation to seaward and cyclonic circulation inside the jet, and of near bottom under-current apparently coincident with bottom mixed layer of Fig. 1.

5. Discussion

a. *Relevant theories.* Despite the usual impression of the Benguela system as a broad sluggish drift, well established theoretical considerations make it clear that a belt of enhanced equatorward flow *should* be associated with the edge of a wide continental shelf in an eastern boundary current system. It follows from the elementary wind-driven Ekman slope current concept as expanded by Sverdrup et al (1942) that the redistribution of mass near the boundary of the system will produce a zone of baroclinicity and a relative current superimposed upon the barotropic wind-driven circulation. These mass redistribution effects will be experienced first over the continental slope and then at the land boundary where a situation predisposed towards coastal upwelling will be set up. It is significant that, as originally indicated by Ekman (1905) and as subsequently re-emphasized by Tomczak (1972), this basic circulation is normally assumed to be driven by easterly winds in the tropics and westerly winds at high latitudes rather than by meridional winds on either side of the basin.

Working from a differing set of premises, the numerical, meridional wind-stress, coastal upwelling models of the O'Brien school (e.g. Hurlburt and Thompson, 1973) have shown that the shelf edge should be characterised by a stronger equatorward filament. However, these models obviously depend

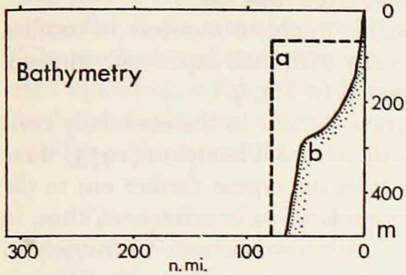

Figure 8.

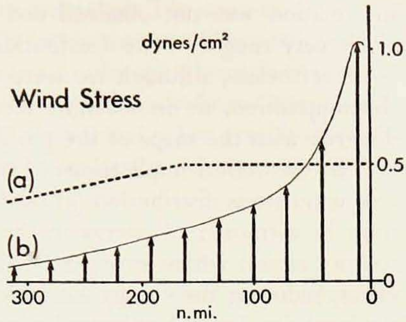

Figure 9.

Figure 8. (a) Model bathymetry assumed by Hurlburt and Thompson (1973) compared with actual bathymetric profile west from Cape Town (b).

Figure 9. (a) Portion of horizontal (east-west) wind profile assumed by Hurlburt and Thompson (1973) compared with suggested local configuration (b). ART pilot's reports, personal experience and an examination of variously smoothed synoptic charts make it clear that there is a rapid decrease in meridional wind-stress west of a near-shore maximum.

quite critically on their input assumptions, the broad shelf case assuming a shelf of 100 km width, depth 65 m and bounded to seaward by a vertical step (Fig. 8a). Even under these exaggerated conditions, shelf-edge activity is only just evident, and the velocity enhancement amounts to no more than a few cm/sec over the general equatorward flow of less than 20 cm/sec. If one were to "plug in" Cape bathymetric specifications (Fig. 8b) it is predictable that the model would show even less shelf edge activity.

Thus although reasoning stemming from both the simple Ekman basin circulation *and* numerical coastal upwelling results point to some enhanced velocity near the shelf edge, these factors either singly or in combination cannot explain the intensity of the jet here demonstrated. Both are secondary features reflecting the shelf-edge bathymetric discontinuity: if the latter is poorly defined the former will probably tend to follow suit.

b. *Horizontal wind-stress profiles.* Although they contain useful pointers and obviously represent steps in the right direction, the C.U.E. numerical models appear to be unsuitable for local adaption until a more realistic model framework can be set up. The differing bathymetric specifications have been mentioned: more important than these are the assumptions as to the impressed windstress.

During the 10 days of ART flying which accompanied this programme, the air-crew were exhorted to make and log repeated drift sight observations in order to obtain some quantitative idea of the horizontal (east–west) wind profile during upwelling. The data were to have been included in a flight report submitted by the pilots. Unfortunately, for reasons which must be accepted, this information was not obtained and an invaluable opportunity to quantify—albeit very roughly—the distribution of wind stress was lost.

Nevertheless, although we were thus unable to obtain numbers to confirm this supposition, we do not think there are many with local experience who will disagree with the *shape* of the profile suggested in Fig. 9.

The theoretical implications of this diagram are that in the essentially curl-free wind-stress distribution (a) used by Hurlburt and Thompson (1973) there must be a transfer of energy in the ocean from the region further out to the inshore region where stronger frictional forces have to be overcome, thus, in effect, reducing the energy available for jet formation offshore. Conversely in the local situation (b), enhanced wind stress near the coast will provide sufficient energy to overcome friction without having to rob momentum resources to seaward and will also provide a surplus of energy which can eventually be fed seawards. Initially this surplus will be used to elevate more cold water onto the shelf, thus building up a store of potential energy upon which the offshore jet will begin to feed, and which will be capable of sustaining the jet even when the upwell-favourable wind-stress is temporarily "switched off" during spells of adverse synoptic activity.

If the jet is geostrophically adjusted, as appears to be the case, its energy requirements are relatively frugal and during spells of prolonged favourable wind-stress, potential energy will accumulate at a rate faster than the frontal jet can utilize it. As a result the front will move gradually seaward. Once it reaches the edge of the shelf, however, the jet will be able to expand downwards and its energy appetite will increase accordingly. If energy consumption exceeds supply the front will retreat landwards and one can imagine an equilibrium situation eventually being established somewhere near the edge of the shelf.

c. *Structural persistence and rate of upwelling estimates.* It is essentially erroneous to imagine the jet "holding up" colder water on the shelf. *But* the fact that a geostrophic situation has been set up *does* mean that the cold water cannot simply slide back into its native depths as soon as favourable wind stress is "switched off". The potential energy of the frontal structure is only dissipated in the various natural inefficiencies of the theoretically divergence free geostrophic situation—a much slower process. Judging by the C.U.E. numerical results (see O'Brien, 1973) which generally deal with smaller scale, lower energy situations, a front such as that illustrated in Fig. 1 above could probably persist in recognisable form for at least a month after favourable wind-stress is switched off. During this period the hydrological character of the surface layer a few tens of meters in thickness may be profoundly changed by processes such as those discussed previously, but the mass of cold water will remain on the shelf. Subsequent spells of favourable wind stress will thus *only need to displace this 30 m film* to produce obvious manifestations of upwelling. This possibly of imminent predisposition towards upwelling should always be borne in mind when rates of upwelling are estimated. The removal of the surface film in one day does not automatically imply that upwelling will continue thereafter at the rate of 30 m/day as long as a similar wind stress is maintained. The mechanics of stationary upwelling differ significantly from those of incipient upwelling, a fact which is not always appreciated when results of vertical isotherm displacement measurements are extrapolated to cover continued upwelling under situations of hydrological stationarity.

d. *The Agulhas Current contribution.* The results of this and many previous surveys show that vestiges of Agulhas Bank (Shannon, 1966) or Agulhas Current (Bang, 1973b) water are almost always found outside the Cape upwell cell in summer. Whether obviously identifiable or not this influx of warmer, lighter water will act to intensify the frontal gradient and we may thus suggest that it is a factor favourable to the maintenance of both front and jet.

Furthermore there is evidence to suggest that the jet becomes a prominant shelf-edge feature well south of the present measurement section. It may thus act as a narrow conduit into which shallow patches of Agulhas water, having been dragged northwestwards by the retreating paw of an Atlantic High atmospheric configuration (Bang and Triegaardt, 1974) are drawn and rapidly displaced northwards, the original patches becoming stretched out into elongated tongues in the process.

6. Conclusion

The very pronounced shelf-edge jet associated with, and drawing its energy from a strong frontal feature 40 miles west of Cape Town constitutes something of an anomaly in the field of upwell research. Although the mechanics of the link are obviously complex, it appears that the disparity between theoretical expectations and actual observations of frontal jet intensity is largely due to the specific form of the local horizontal wind profile. The situation of maximum wind velocity at the coastline implies that a surplus of wind-stress energy is available over and above that required to overcome the greater inshore frictional forces of the oceanic circulation. This energy is ultimately utilized in accelerating the shelf-edge jet.

From the figures provided it will be appreciated that the shelf-edge jet (may we call it the Good Hope Jet?) at times constitutes a substantial element of the gross South Atlantic circulation, even if its northward transport is locally compensated for by adjacent circulations. If the intensity of the Jet is, in fact, predominantly a function of local wind-stress it follows that the contribution of the localized (meridional) Cape South-easter to the driving forces of the whole South Atlantic basin is more important than has hitherto been realized. It is obvious therefore that more attention will have to be paid to such critical meteorological inputs before serious Benguela model studies can be initiated.

Finally it should be stressed that the present series of investigations deal specifically with the *southern* (Cape) Benguela system. Most of our classical knowledge is based on results obtained in the northern (Walvis Bay) portion of the system. The two areas are oceanographically quite different and any extrapolation of results from one to the other should be avoided. In particular the lower latitude coastal wind system tends to exhibit strong diurnal variations in direction, thus reducing its integrated wind stress efficacy: this is not the case in the south.

Acknowledgments. We would like to thank our respective Directors for their encouragement and support, Mr. David Cram and his assistants for laying on the ART coverage and Miss Mary Smith of the JOINT-1 Secretariat, Las Palmas, for typing this manuscript. The work was supported jointly by the S.A. Department of Industries and the Council for Scientific and Industrial Research.

REFERENCES

Andrews, W. R. H.
1974. Selected aspects of upwelling research in the southern Benguela Current. Tethys (in press).

Andrews, W. R. H. and D. L. Cram
1969. Combined aerial and shipboard upwelling survey in the Benguela Current. Nature, *244*: 902–904.

Andrews, W. R. H. and G. A. Visser
1974. The upwelling system off the Cape Peninsula: I. Short term features. Investl. Rep. Div. Sea Fish. S. Afr. (in press).

Bang, N. D.
1971. The southern Benguela Current region in February, 1966: II. Bathythermography and air/sea interactions. Deep-Sea Res., *18*: 209–224.

Bang, N. D.
1973a. Oceanic environment of South Africa. In: Std. Encyclopaedia of S. Africa, *8*: 282–286, Nasou Press, Cape Town.

Bang, N. D.
1973b. Characteristics of an intense ocean frontal system in the upwell regime west of Cape Town. Tellus, *25*: 256–265.

Bang, N. D. and D. O. Triegaardt
1974. Ridging persistences of the South Atlantic High in relation to wind-stress advection of Agulhas Current fragments into the Benguela system. Notos, S. A. Weather Bureau (in press).

Carter, Howard
1923. The Tomb of Tutankhamen. Vol. 1, Cassell, London, 300 pp.

Cram, D. L.
1973. How A.R.T. could assist the search for Cape mackerel. S. Afr. Ship. News & Fish. Ind. Rev., *28*: 82–83.

de Decker, A. H. B.
1970. Notes on an oxygen depleted subsurface current off the west coast of South Africa. Investl. Rep. Div. Sea Fish. S. Afr., *84*: 1–24.

Ekman, V.W.
1905. On the influence of the earth's rotation on ocean currents. Arkiv. Matematik Astron. Fysik, *2* (11).

Hurlburt, H. E. and J. D. Thompson
1973. Coastal upwelling on a beta plane. J. Phys. Oceanogr., *3*: 16–32.

O'Brien, J. J.
1973. Models of coastal upwelling. Proc. NAS Symp. on Numeric. Models of OC. Circ., U.S. Nat. Acad. Sc., 99 pp.

Shannon, L. V.
1966. Hydrology of the south and west coasts of South Africa. Investl Rep. Div. Sea Fish. S.Afr., *58*, 62 pp.

Sverdrup, H. U., M.W. Johnson and R. H. Fleming
1942. The Oceans. Prentice-Hall, New York, 1060 pp.

Tomczak, M. (Jr)
1972. Problems of physical oceanography in coastal upwelling investigations. Geoforum, *11*: 23–34.