Upwelling along the South Coast of the Cape Province, South Africa

E.H. Schumann, L.-A. Perrins and I.T. Hunter

National Research Institute for Oceanology, CSIR, P.O. Box 320, Stellenbosch 7600, South Africa.

Although upwelling along the south coast of the Cape Province does not have the same economic significance as on the west coast, it is of importance to local industries. Moreover, analysis shows that there are unique features associated with the prevailing winds and coastal and bottom topography. Satellite imagery combined with coastal measurements of wind and sea surface temperature has been used to investigate the upwelling. It is found that the prominent capes in the eastern half of the region are important in initiating the upwelling, and a simple theory is advanced to explain the observations.

Hoewel opwelling langs die Kaaplandse suidkus nie dieselfde ekonomiese betekenis het as langs die weskus nie, is dit vir die plaaslike nywerhede van belang. Die analise toon bowendien dat dit unieke kenmerke het wat met die heersende winde en die seebodemtopografie verband hou. Satellietbeelde en metings langs die kus van die wind en van die see se oppervlaktemperatuur word by die opwellingsondersoek benut. Daar is vasgestel dat die vooruitstekende kape in die gebied se oostelike helfde 'n belangrike rol speel by die veroorsaking van die opwelling. 'n Eenvoudige teorie word aan die hand gedoen om die waarnemings te verklaar.

Introduction

The process of upwelling involves the vertical upward transport of water from deeper to shallower reaches of the ocean. A variety of mechanisms may operate, with the end result possibly being of great economic importance. Some of the world's major fishing industries are dependent on upwelling, because the process brings nutrients into the euphotic zone, thus starting the whole food chain from phytoplankton to the large predators.[1] Prime examples of upwelling occur off Peru with its associated 'El Nino' phenomenon,[2] northwest Africa,[3,4] the west coast of the USA,[4,5] and off the Cape west coast[6,7] and South West African/Namibian coast.[8]

Along the Cape south coast, upwelling does not have the same economic significance as it does on the west coast. None the less, localised enhancement of primary productivity indirectly benefits the local fishing activities centred on sole and hake, although mention should also be made of fish being stunned and killed by the sudden advent of cold water.[9] Moreover, some of South Africa's premier holiday resorts lie on this coast, and events which affect bathing and recreational conditions are of obvious economic importance. The results given here on upwelling in the region are qualitative and should be regarded as only preliminary. Even so, the processes involved are of considerable interest, and show that there are distinctive features associated with the local topography and dominant wind conditions.

Upwelling processes

The upwelling to be considered here is specifically that occurring along a coastline, and generated by the local wind. It is a situation that has been studied for many years, and there are many papers and reviews on the topic.[10,11] The mechanism is represented in Fig. 1. The longshore wind shown moves surface waters offshore, with replacement by subsurface water occurring in the form of an adjustment drift.[12] The thermocline demarcates the divide between the warmer surface waters and the colder, deeper waters; when this breaks the surface, a well-defined surface frontal zone forms with the colder water on the landward side. The reverse condition of downwelling arises when the wind blows in the opposite direction.

There are many ramifications of this simple picture. The effect of wind is not precisely understood. The general results of the well-known Ekman theory appear to apply,[13] with water flow in the upper tens of metres to the left of the wind direction in the southern hemisphere (the Ekman drift shown in Fig. 1). However, well-defined Ekman spirals are rarely observed[14] because of stratification, the variation of physical characteristics with depth and time, and the influence of ambient currents and other dynamical effects originating outside the observation area. In relatively shallow water, bottom frictional effects will cause the resulting flow to tend to align with wind direction. An alongshore pressure gradient is set up which produces geostophic flow (a balance of the pressure gradient force and the apparent Coriolis force due to water movement across the surface of a rotating earth). The extent to which the balance is attained, and the offshore influence of the coastal upwelling depend on the ocean structure and water depth.[15] Generally, the upwards motion of the thermocline is confined to a coastal band a few tens of kilometres wide.

Of interest here is the longshore current, in the direction of the wind, that is generated by the offshore pressure gradient. The position of the core of this current depends on the state of the upwelling process; experimental measurements indicate an association with the upwelling front.[15,16] The time scales associated with wind-

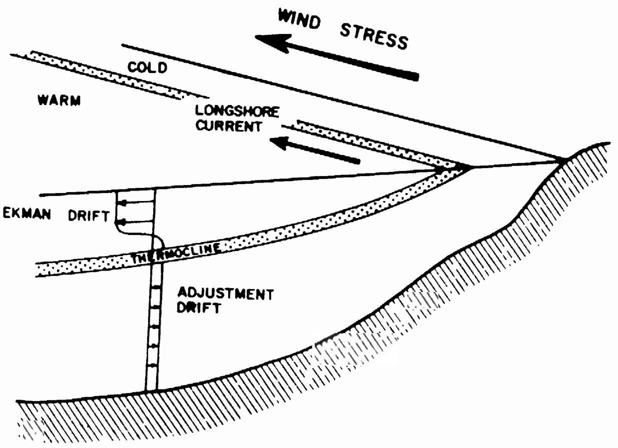

Fig. 1. A diagrammatic representation of processes which operate during upwelling. The Ekman drift in the upper layers, caused by wind stress at the water surface, is compensated for by adjustment drift in the deeper layers; this causes colder water to upwell at the coast. The replacement of water is not complete, however, and the pressure gradients set up by a falling sea surface at the coast cause longshore currents to flow.

induced upwelling depend on local conditions such as ocean structure, bottom topography and past history. Large thermocline displacements can occur within hours of the onset of a suitable strong wind; however, once establsihed, the upwelling may take several days to dissipate.[15]

Data

The data used in this investigation come primarily from satellite imagery. The NOAA 5 and 6, Tiros N, Meteosat and Nimbus 7 satellites all have sensors operating in the infrared at about 11 μm, and thus are capable of measuring sea surface temperature.[17] Although the absolute values of such measurements may not be very accurate (they are correct to within a few degrees Celsius), it is the relative values which are of importance here. Variations of less than 1°C can be distinguished in sea surface temperatures from satellite imagery, enabling upwelling patterns to be easily recognised. Of course, this is true only if the upwelling process has advanced far enough for the colder water from below actually to reach the surface.

The satellite image must be enhanced so as to bring out the oceanic features of interest. Unfortunately, the 11 μm radiation cannot penetrate cloud cover, which means that on occasions the area of interest may be obscured. Sometimes a light sea fog may also form, making it difficult to distinguish whether features in the image record sea or air phenomena. Fortunately, however, on most of those occasions reference to the visual band carried by many satellites can solve the problem. It is clear from the previous section that if the upwelling processes are to be understood, the coastal wind field must be known. In this respect the data available are not satisfactory, especially since the wind offshore may be substantially different from that measured at coastal weather sites.[18] The only suitable data available are those from the lighthouses at Cape St Blaize, Cape St Francis and Cape Recife and the synoptic charts published by the Weather Bureau. The lighthouses suffer from a lack of suitable measuring equipment (wind speeds and directions are estimated by the lighthouse keepers). The charts are produced only once daily, while considerable changes in wind conditions could have taken place between readings. Ideally, sea surface temperatures taken *in situ* are required to refine studies of the upwelling phenomenon. In this respect daily sea surface temperatures taken at the Storms River mouth in the Tsitsikamma coastal National Park (R. Crawford, personal communication) proved invaluable.

Occurrence of upwelling

Satellite imagery from Nimbus 7, Tiros N, NOAA 5, and Meteosat I was examined covering a three-year period starting in the summer of 1978. It is not a straightforward matter to classify upwelling phenomena from satellite images. The first four satellites listed above make different passes on each orbit, and thus may cover different parts of the Cape coast. In addition, if the region of interest lies to one side of the swath, the resulting image may be heavily distorted, thus making identification of features more difficult. Moreover, clouds or fog may cover parts of the region. Other circulation patterns which do not seem to have any connection with upwelling events along the coast also occur in the area of the continental shelf. Thus occasionally features originating in the Agulhas Current penetrate onto the shelf.[19] At other times patterns can be seen in the shelf area which have no obvious origin, especially if no imagery is available of their early stages of formation.

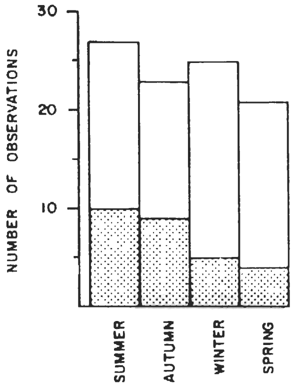

Fig. 2. Frequency of occurrence of upwelling. The total number of suitable observations in each season is shown, with the number of upwelling events indicated by the shaded part of each bar. Summer is taken as the three months December to February, autumn as March to May, winter as June to August, and spring as September to November.

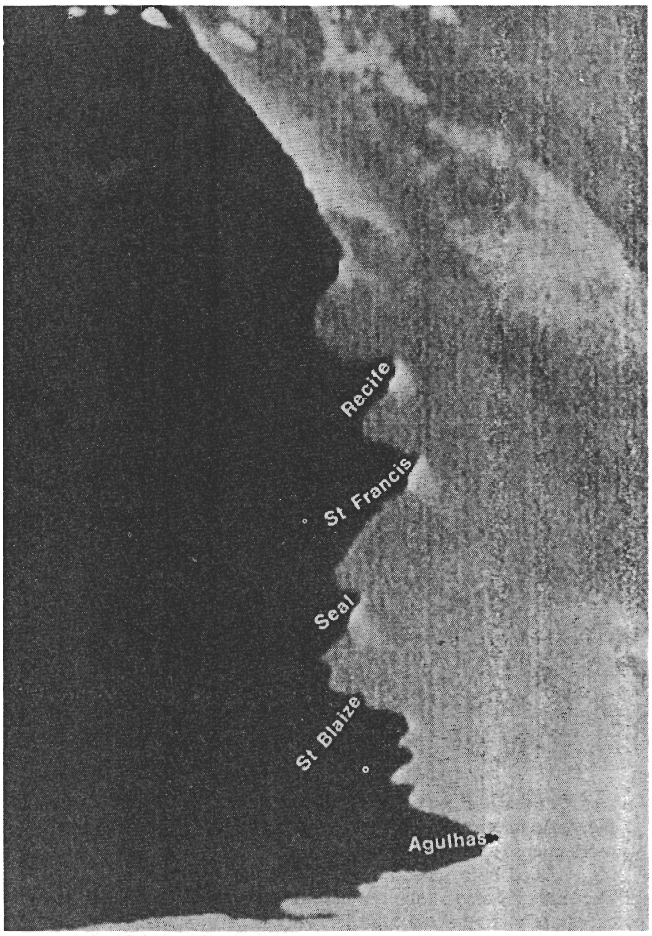

Fig. 3. A thermal infrared image taken on 13 December 1979 by the Tiros N satellite. Colder water is shown as a lighter shade of grey and upwelling is clearly evident off Capes Recife, St Francis and Seal. The distortion results from the imaging process.

The various satellites have different resolutions. The Nimbus 7 picture element (pixel) size is about 800 m square, the NOAA and Tiros N satellites have pixel sizes of about 1 km square, while that of Meteosat I is approximately 8 km square. The specification of an upwelling event is somewhat subjective; none the less, information can be obtained on the frequency of occurrence of upwelling. A total of 96 suitable images were identified over the three-year period, with 28 of these showing upwelling at some point along the south coast (each day was considered separately, irrespective of past history). With these small numbers it is not possible to give monthly statistics; Fig. 2 is a histogram showing seasonal variations. The indications are that upwelling occurred with twice the frequency during December to May than in other months.

There are two aspects of this analysis which can affect the above conclusion. First, upwelling events may be obscured by clouds, and therefore not recorded. Secondly, the vertical ocean structure on the western half of the Agulhas Bank is much more mixed in the winter months than in summer (G.A. Eagle, personal communica-

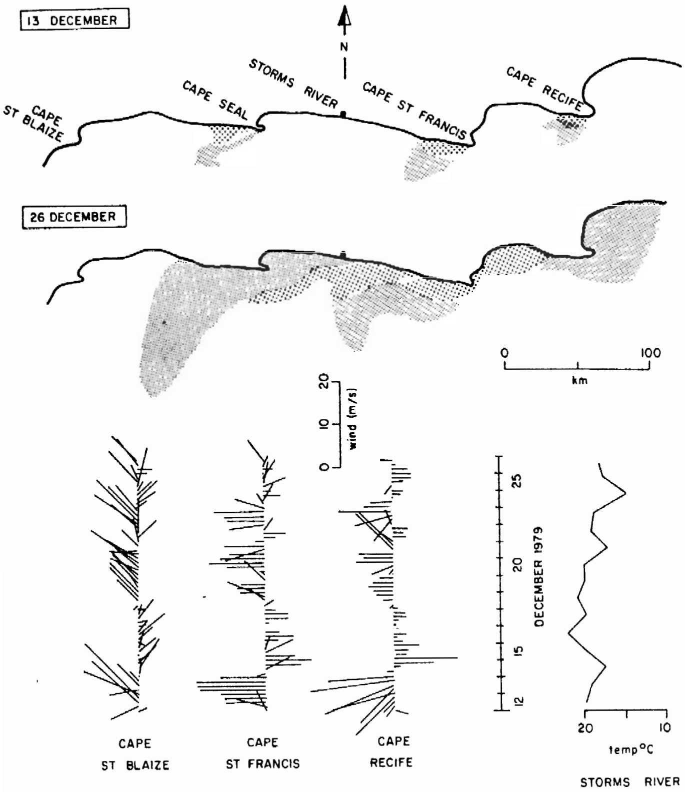

Fig. 4. An interpretation of the upwelling shown in Fig. 3, with the more intense upwelling indicated by darker shading. The upwelling revealed by a second Tiros N satellite image, taken on 26 December, is also shown. Wind vectors measured at the three capes are given below, together with sea surface temperatures measured at Storms River mouth.

tion). If there is no well-defined thermocline, or if the thermocline does not break the surface, there will be no clear identification of upwelling from surface temperature gradients. However, surface fronts will appear between mixed and stratified regions.

In order to illustrate upwelling dynamics, three case studies have been selected and are discussed here in detail. Although the selection is somewhat subjective, it has been done to demonstrate particular aspects of the phenomenon; in particular, the relationships between wind, topography and upwelling.

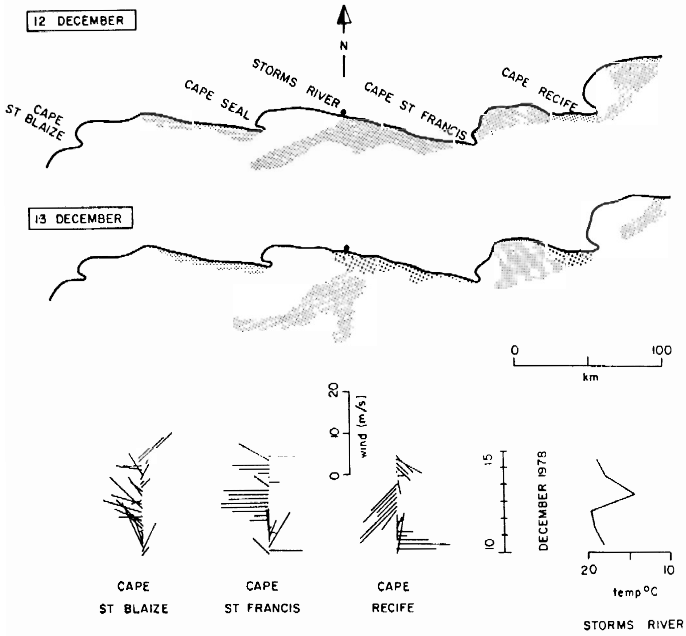

Fig. 5. As for Fig. 4, but with the infrared images recorded by the Meteosat I satellite on 12 and 13 December; on the latter day a NOAA 5 satellite image was also available.

Figure 3 is a satellite image which typifies an important aspect of upwelling along the Cape south coast, namely, the part played by the prominent capes and crenulated bays, particularly on the eastern side of the region. It is clear that the upwelling in this case is concentrated off Cape Recife, Cape St Francis and Cape Seal. Figure 4 shows the sequence of winds reported at Cape St Blaize, Cape St Francis and Cape Recife between 12 and 26 December 1979. Reference to weather charts indicates that early on 12 December a bud-off high-pressure system moved in from the west behind a front which had moved through the area on 11 December; this caused winds with a strong easterly component to blow at all three capes for the next 48 hours. Also given in Fig. 4 is an interpretation of the upwelling of 13 December shown in Fig. 3, which was probably caused by the winds described above. Sea temperatures at Storms River mouth decreased by about 2°C on 14 December as a result of the upwelling.

On 14 and 15 December, westerly winds blew in association with the passage of a series of fronts; the sea temperatures at Storms River mouth indicate that these must have reversed the upwelling process. Easterly winds became re-established only on 18 December, when the next bud-off high-pressure centre moved south of Cape Agulhas. The period to 23 December was then marked by winds with a fresh to strong easterly component, with a short break early on 22 December as a coastal low-pressure system passed through. The easterly winds caused a gradual decrease in sea temperatures at Storms River mouth, with a drop of 4°C on 24 December. Winds with a more westerly component, particularly at Cape Recife and Cape St Francis, appear to have reversed this process again after a day. The satellite image taken on 26 December probably shows the legacy of these past upwelling events, with a clear indication of a movement offshore towards the west.

The second case is based on the results of satellite imagery on 12 and 13 December 1978 (Fig. 5). During much of this time a ridge of high pressure was established off the Cape south coast. This resulted in predominantly easterly winds blowing, broken only briefly by two coastal lows which moved through on about 10 and 14 December. Strong easterly winds were recorded on 8 and 9 December, and the image for 12 December shows traces of upwelling possibly associated with these winds. The image for 13 December records evidence of new upwelling, probably as a consequence of the strong easterly component winds that started blowing on the previous day. The upwelling was concentrated off Cape St Francis and Cape Recife; possibly the winds further west were not strong enough to initiate upwelling.

Sea surface temperatures measured at Storms River mouth, which dropped sharply on 13 December, reflect this upwelling behaviour. The increase in temperature on 14 December indicates that the event was short-lived, no doubt because the wind had moderated.

The third case is based on a sequence of images taken over a period of five days in January 1979, although suitable observations were possible only on three of the days (Fig. 6). Strong easterly wind components were established on the coast on 4 January, disturbed only by a coastal low which passed through from late 5 January to late 6 January. It is noteworthy that the coastal low showed up most clearly in the wind records of the more easterly lighthouses.

The upwelling was already well developed by 5 January, with large expanses of cold water evident in the areas of Cape Seal and Cape St Francis, and of more limited extent at Cape Recife. The temperatures measured at Storms River mouth show a marked drop of over 5°C from 4 to 5 January. The effect of the westerly winds associated with the coastal low is evident from the subsequent rise in temperature. However, by 8 January new easterly winds were causing a new patch of upwelling at Cape St Francis; this was

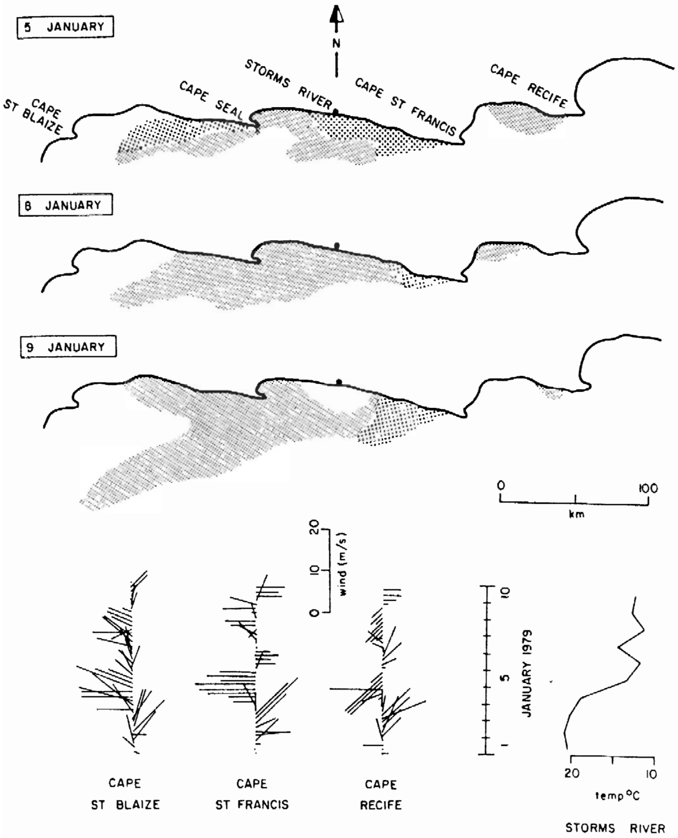

Fig. 6. As for Fig. 4. The infrared images were recorded on all three occasions by Meteosat 1.

reflected by the plunging temperatures at Storms River mouth. It is of interest to note that the weaker winds at Cape Recife did not cause any marked upwelling there.

The three case studies above have demonstrated the importance of the capes and bays in the upwelling processes along the Cape south coast. In addition, winds with an easterly component appear to be essential, as no cases of upwelling were found to occur in their absence. On the other hand, there were a substantial number of other instances when easterly winds blew but no upwelling could be discerned. It is therefore not sufficient to specify merely that easterly winds will cause upwelling; other factors such as the strength and duration of the wind and past history need to be considered. In addition, the upwelling could have been initiated, but need not have affected surface conditions. Most of these factors were unknown in this study and therefore their roles could not be assessed.

A simple explanation is given here of the roles of the capes and easterly winds in the observed upwelling. Figure 7 shows details of the structures and bottom topography of Cape Recife, Cape St Francis, Cape Seal and Cape St Blaize. Upwelling appears to favour the first three sites. Figure 8 illustrates the processes which it is suggested operate at such sites to produce upwelling. In relatively deep water the easterly component of wind will cause an Ekman drift southward in the upper layers of the ocean. However, the water depth on the inner (northern) bay side of the cape is generally much less than that on the southern side, and consequently the surface flow there will align more closely with wind direction, that is, westward. In the bay itself downwelling will occur, with water circulation as shown. On the southern side of the cape the abrupt topography will cause the surface flow to be predominantly offshore. Under the influence of water flow in the bay, the vicinity of the cape will become a region of surface divergence, in which upwelling will be accentuated. Associated with this upwelling, on the southern side the coastal jet will develop. As a consequence, upwelling will tend to start at the cape, and then progress westwards.

The situation at Cape St Blaize (Fig. 7) can ben seen to be different from the above description. Although the circulation in Mossel Bay may develop as discussed above, the topography to the south is not suitable for upwelling. It is not as deep as at the other capes, and the longshore extent is limited by the next bay (Vlees Bay), culminating in Vleespunt. Indeed, the circulation in Vlees Bay may be such as to oppose the onset of upwelling at Cape St Blaize.

Discussion

The results presented above have indicated several features of upwelling along the Cape south coast. In particular, the importance of some of the capes and bays in initiating upwelling has been

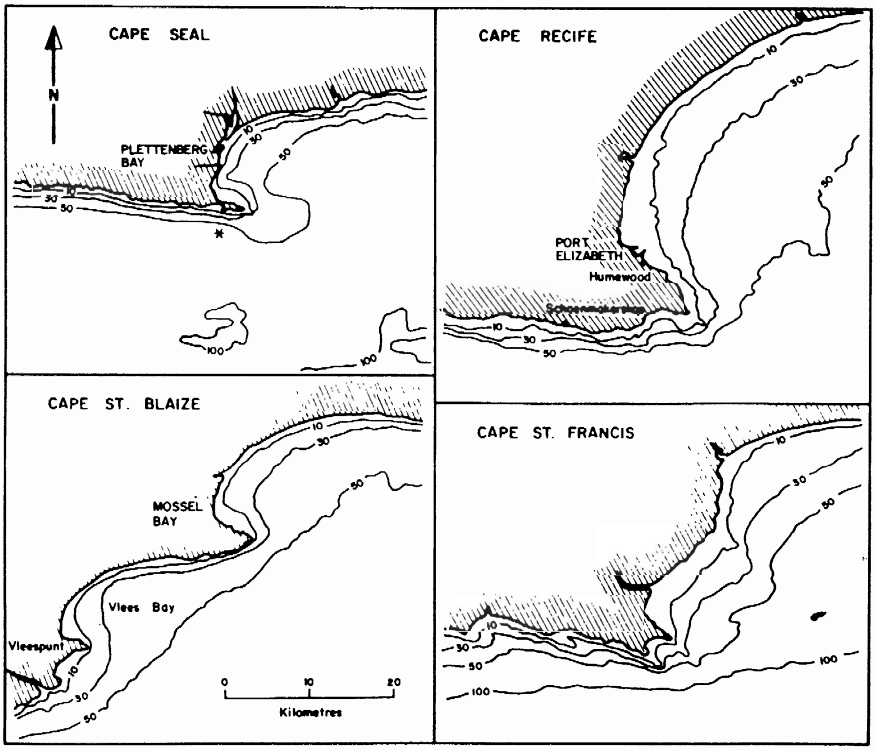

Fig. 7. Details of structures and bottom topography at four capes along the south coast. The position of the station where the temperature profile shown in Fig. 9 was recorded, is indicated by an asterisk off Cape Seal.

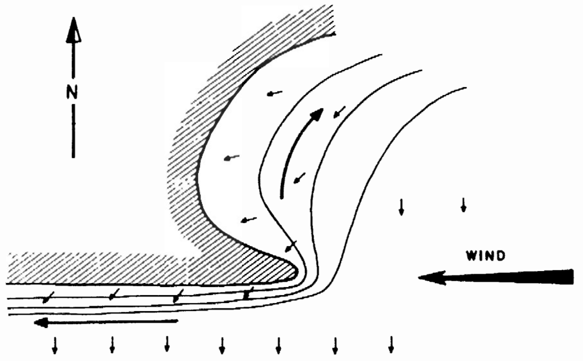

Fig. 8. Proposed processes operating at a cape to produce upwelling. The surface wind induces an Ekman drift (small arrows) in the surface layers, while resulting pressure gradients generate alongshore currents in the water column (long arrows).

demonstrated; this type of topography may not be essential, but is clearly desirable.

The association of a 'cold current' with southeasterly winds along the Cape south coast is well known. In a study at the Knysna estuary, Korringa[20] postulated that the cold water originates south of the sub-tropical convergence. Given present knowledge of the Agulhas Current[21] this is highly unlikely, and it is probable that the coastal jet could have brought the colder, upwelled water to this particular site. Indeed, the influence of the Agulhas Current on the Cape south coast is likely to be minimal. Upwelling generally arises a few tens of kilometres offshore, whereas the main flow of the Agulhas Current generally lies further out to sea, beyond the shelf break. It is possible that Agulhas Current water reaches over the whole Agulhas Bank area in a series of complicated mixing processes.[22]

Peffley and O'Brien[23] undertook a three-dimensional simulation of upwelling off Oregon, and concluded that the influence of bottom topography dominated that of coastline irregularities. They found that the relatively strong upwelling experienced near Cape Blanco was due more to local bottom topography than to the cape itself. Off the Cape south coast, the situation is markedly different as regards the nature and orientation of coastlines and wind direction. However, the associated bottom topography, discussed above, is also of vital importance.

Winds with an easterly component are generally required to initiate upwelling. These winds occur predominantly in summer, when the zone of maximum anticyclonic activity has moved south;[24] available information indicates a greater frequency of upwelling at this time. However, this conclusion should be regarded as tentative. Most of the observed upwelling took place in the eastern half of the region. Further to the west the orientation of the coastline changes to lie more westsouthwesterly, and this change combined with different bottom topography may be enough to preclude a similar upwelling mechanism operating to that described above.

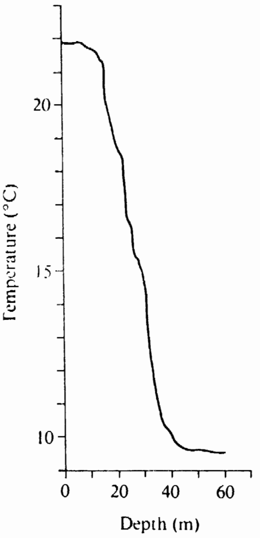

Fig. 9. A temperature profile recorded in February 1982, at the station position shown in Fig. 7.

Temperature structure also plays an important part in upwelling. Figure 9 shows a profile recently recorded off Plettenberg Bay, the actual station position being indicated in Fig. 7. This indicates a strong thermocline, with a drop in temperature of about 11°C between 15 and 35 m depth. With this temperature gradient, upwelling will not need to proceed very far before marked temperature changes are recorded at the shore.

There are few measurements available of the resulting sea surface temperatures on either side of a cape during upwelling. Those taken at Humewood Beach in Port Elizabeth and at Schoenmakerskop (see Fig. 6) have indicated that they may differ by more than 5°C (L. Beckley, personal communication). Such variations could have profound effects on the biota along a coast subject to upwelling.

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