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On a Thermal Feature of bottom water during upwelling on the East Coast of India

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1. Introduction

The phenomenon of upwelling, in which subsurface layers in the sea move upward towards the surface, has been reported (La Fond 1954a, 1955). It is now possible to discuss an unusual thermal feature in the light of additional data derived from the Andhra University oceanographic research programme conducted along the east coast. The development of an isothermal layer along the bottom across the continental shelf off Waltair has been observed, and the probable reasons for its formation are discussed.

2. Data

On several occasions vertical temperature sections were repeated across the shelf, in order to study the vertical circulation. It was observed that in the fall the thermocline tilted upward with respect to distance from the coast. In this season of sinking there is a deeper layer of relatively warmer water on the inner part of the continental shelf as compared to that found over the outer shelf.

In early February of this year during the quiet weather, the bottom of the hydrospheric layer levelled off, being about equal in depth all across the shelf. At the end of the month and in the beginning of March the wind direction steadied from the southwest and increased in strength. By 7 March the isotherms were tilted up the shelf, and were twice as deep on the outer shelf as they were near shore. The horizontal temperature gradients continued to increase until the isotherms intersected the surface on the inner part of the shelf. However, at this time, the unique feature which developed in the thermal structure was an isothermal layer near the bottom. This feature was observed in earlier records by A. A. Rama Sastry and was mentioned by La Fond (1956). It consists of a layer of water over the central and outer shelf in which the temperature is virtually the same vertically. In other words the water is mixed. It first appeared as a thin layer at the bottom extending up only 5 or 10 feet. However, by March, as shown in the lower part of Fig. 1, the thickness of the isothermal layer was about 35 feet, 7 miles off shore. It can also be seen that the nearshore temperature structure had a slight negative gradient. The same was true farther off shore at a depth of 80 metres. At this period the isothermal water along the bottom was confined to depths of between 50 and 80 metres. As the season progressed, the layer became still thicker. Although the water was nearly isothermal vertically it was not so horizontally. The bottom temperature increased shoreward, as shown by the temperatures inserted in the lower part of Fig. 1.

3. Discussion

The formation of the layer is of interest in that it must be formed *in situ* by some physical means. There is no possibility of its being caused by atmospheric effects, such as wind mixing or atmospheric cooling (La Fond 1954b). This isothermal feature develops at the bottom and has no

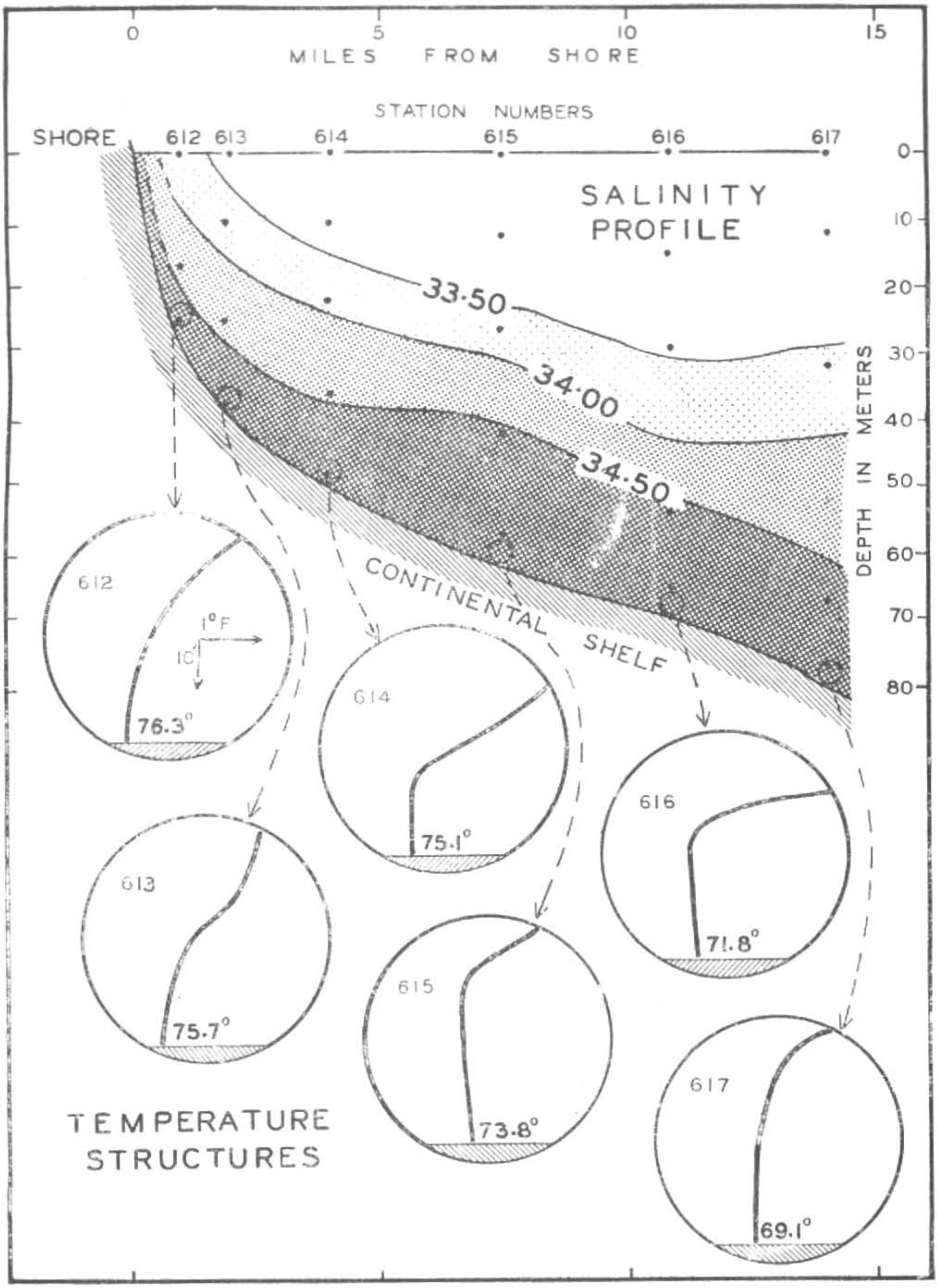

Fig. 1. The salinity profile and vertical temperature structures of the coastal waters off Waltair (7 March 1956)

Upper part—Isohalines over the continental shelf indicating the upwards tilting towards shore produced by upwelling (courtesy of Prof. P. N. Ganapati)

Lower part—Enlarged *temperature versus depth* curves observed at the six indicated locations near the bottom along the continental shelf apparent connection with the surface.

There appear to be four possibilities by which this layer may be formed. They are—(1) by selective advection of water of one temperature, (2) by advection or formation of relatively heavy water at one level which will set up vertical convection currents, (3) by advection or formation of relatively light water immediately at the bottom which will set up vertical convection currents and (4) by turbulent mixing along the bottom.

Selective advection—If the selective advection hypothesis is to be accepted, one would look for a submarine sill over which water at one level would spill, as in a waterfall, into a basin. However, from a study of the bathymetry of the area, there appears to be no sill or basin-like structure in any part of the eastern Bay of Bengal. Another feature contending against this advection hypothesis is that the temperature increases from 69·1°F at 15 miles out to 75·1°F at 4 miles from shore. A uniform temperature would likely form throughout the isothermal zone if advection of a single temperature water was occurring. This is not the case.

Vertical convection—The second and third hypotheses, namely, vertical convection both downward and upwards, may be considered together. The first postulates that heavy water forms at a mid-depth which is more dense than the water below. Being unstable it sinks and causes vertical mixing. The other hypothesis pre-supposes a lighter water on the bottom which rises to create the same mixing effect. Of the two possibilities the former seems more plausible.

Such a situation could develop over the shelf when colder water coming up the shelf cools any overlying high salinity water existing in the region. Thus an unstable layer would form. However, the water on the shelf at this season is normally of lower salinity than is the upwelling water.

Another feature which does suggest vertical convection is the slightly positive gradient observed in March 1956. The water in the mixed layer at stations 615 and 616 showed a slightly higher temperature at 35 feet above the bottom than it did immediately at the bottom. Similar weak positive gradients are found at the sea surface during fall and winter cooling. It seems possible that the water is being cooled and, when sufficiently dense, overturns, thereby creating the isothermal layer observed. The other possible explanation is a warm water intrusion at the bottom which would develop a similar gradient. Both processes are feasible and the stability of the water was observed to be low.

Turbulent mixing—The fourth hypothesis, namely, turbulent mixing across the bottom, appears to be the most likely. The mixing of water along river bottoms is easily visualized. It depends upon the speed of flow, and the roughness of the bottom. Upwelling, however, is a very slow process and is not subjected to strong turbulent mixing. However, there is at this time another current which is developed by the southwest monsoon winds and which flows up the coast. This current begins about January and lasts upto July. In the spring it has been observed to attain a speed of 2 to 3 knots. At first only the surface waters are affected, but as the season progresses the bottom water also moves to the northeast. Although no direct measurements of bottom currents over the shelf are available they can be deduced from the wire angle subtended when lowering instruments from a drifting ship. If the wire angle is low (the wire hangs vertically), the surface and bottom currents are nearly the same. A large wire angle indicates a difference in current. The observed wire angles at stations on the central part of the shelf were low in April, which means the current near the bottom was comparable to that at the surface.

Other evidence of current along the bottom is from the type of sediments observed. Mahadevan and Poornachandra Rao

(1954) found that a shelly sediment exists on the bottom between 31 and 70 fathoms. Also, coarse sand is found in the neighbourhood of 30-35 fathoms. The finer sediments, mud and silt, are apparently being washed away and the presence of shell and coarse sand are indicative of relatively strong currents.

It is also known that the bottom between 30 and 50 fathoms is not smooth (Kukkuteswara Rao and La Fond 1954). The echo sounder traces of shelf profiles show peaks of 2 to 3 fathoms. This was further substantiated when dredging at 35 fathoms by having the dredge repeatedly 'hang up' on promontories on the bottom. At this level the bottom is decidedly rough.

Therefore from the foregoing evidence of relatively strong along-shore bottom currents and the fact that the bottom itself is rough, it seems likely that turbulent mixing takes place near the bottom. This is further substantiated by the mixed water first appearing at the immediate bottom and then gradually becoming thicker.

4 Conclusions

The unique formation of an isothermal layer at the bottom over the central part of the continental shelf seems to be caused by two agencies. The first is upwelling, which introduces water of nearly the same density and perhaps creates instability in a layer near the bottom. The second, and probably the more important, is turbulent mixing, a result of relatively strong currents flowing over a rough sea bottom. This mixing starts during the initial stages of upwelling and centres around 35 fathoms. It is likely that from the location and thickness of the isothermal layer, the position of maximum current along the continental shelf in this region can be deduced.

REFERENCES

Kukkuteswara Rao, B. and La Fond, E. C.	1954	*Andhra Univ. Mem. Oceanogr.*, **1**, pp. 78-85.
La Fond, E. C.	1954a	*Ibid.*, **1**, pp. 117-121.
	1954b	*Ibid.*, **1**, pp. 94-101.
	1955	*Curr. Sci.*, **24**, pp. 258-259.
	1956	*Ibid.*, **25**, pp. 40-41.
Mahadevan, C. and Poornachandra Rao, M.	1954	*Andhra Univ. Mem. Oceanogr.*, **1**, pp. 1-35.