

## Reference Depth for Geostrophic Computation—A New Method

M J VARKEY & J S SASTRY

National Institute of Oceanography, Dona Paula, Goa 403 004, India

Received 28 July 1987; revised received 24 September 1987

Various methods are available for the determination of reference depth for geostrophic computation. A new method based on the vertical profiles of mean and variance of the differences of mean specific volume anomaly ( $\delta \times 10$ ) for different layers of the water column for various pairs of stations is presented. The results agree well with published information for a region in the Indian Ocean.

Fomin<sup>1</sup> reviewed various aspects of geostrophic computations exhaustively and the methods developed by Defant and Parr seem to give more dependable values as they are based on the basic computed parameter density. Parr's method is based on the vertical profile of the gradient,  $\Delta Z/\Delta\sigma_t$ , whereas Defant's method is based on the vertical distribution of differences in the dynamic depths of isobaric surfaces. The different view points of various workers, as brought out by Carl Wunsch<sup>2</sup>, can, perhaps be summarised only by stating Worthington's conclusion<sup>2</sup> that the geostrophic assumption is not correct. It is also known<sup>2</sup> that the search for a level of no motion is ad hoc and highly controversial. The search for an absolute level of no motion is perhaps futile and the solution seems to be only an approximation to a level of no motion from a level of least motion. A method to identify the level of least motion from the very basics is presented here. It is also shown that for the present study area the layer of least motion is practically a layer of no motion. The present method, one way, takes into account the vertical density distribution at a station and the differences in dynamic depths between pairs of stations.

### Methods

The specific volume anomaly of seawater is defined as<sup>3</sup>,

$$\delta = \alpha_{s,\theta,p} - \alpha_{35.0,p}$$

Since  $\alpha_{35.0,p}$  defines a standard global barotropic ocean,  $\delta$  at any depth(p) anywhere on the globe is the variation of that point from the standard ocean. This parameter,  $\delta$ , is the source of the thermohaline anomalies which give rise to the baroclinicity and hence to the observed field of motion. In dynamic comput-

ations a mean specific volume anomaly ( $\bar{\delta}$ ) is computed for a layer. Using this  $\bar{\delta}$ , the dynamic depth anomaly,  $\Delta D$  is computed for different layers of various thicknesses from surface to deeper layers.

When currents at any level are computed by integrating the thermal wind equation<sup>2</sup> in relation to a particular reference depth, the velocity of the reference level enters the expression as a constant. Generally, in geostrophic computations, the reference level is kept deep in the oceans beyond seasonal influences so that the velocity of the reference level could be assumed to be zero. This interpretation is based on the 'thermal wind' equation. Since  $\bar{\delta}$  is a measure of the baroclinicity at one point, the difference in  $\bar{\delta}$  values between 2 stations is a measure of the potential for motion at a particular level. Hence, from physical reasoning alone without interpreting the 'thermal wind' equation mathematically, it could be understood that a vertical profile of the means of the differences [ $\bar{\delta}(A) - \bar{\delta}(B)$ ]  $\times 10$  between different station pairs for various layers is a measure of the absolute potential without reference to any level.

### Results and Discussion

The potential of motion at different levels between various pairs of stations, configured in all possible ways (Fig. 1), irrespective of distances between stations (within valid geostrophic limits only) and different station alignments is computed. In areas of steady (unidirectional) currents, it would be better to consider pairs of stations aligned in the same direction. It should be mentioned here that in the present selected area (Fig. 1) in the Bay of Bengal, currents from two or three directions are possible at least in the surface layers due to the presence of the islands of Sumatra and Great Nicobar. In the Bay of Bengal the currents above about 1500 m are strongly seasonal<sup>4</sup>. Hence all the available data (as

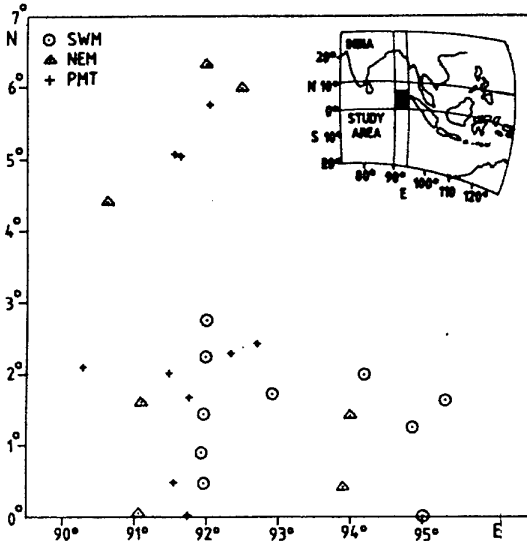


Fig. 1—Stations' locations [○ - SWM, Δ - NEM, + - PMT]

Table 1—Details of Stations Used for Computations

Seasons	No. of sts	No. of pairs sts	No. of pairs with deep profiles (> 2000 m)
SWM	10	29	10
NEM	7	8	2
PMT	11	30	18

on January 1985 at NODC Washington) for deep stations only are grouped together seasonwise to get maximum number of pairs of stations. The seasons are grouped as southwest monsoon (SWM, June-August), northeast monsoon (NEM, November-February) and postmonsoon transition (PMT, September + October). The condition of simultaneity of observations is disregarded assuming seasonal steadiness of currents, as the present interest is limited to an investigation of the depth of reference level whose variations between seasons are of nominal consequences only as shown later. It is also pertinent to mention that this area is comparatively shallow (< 5000 m). Table 1 shows details of the pairs of stations used for the computations.

The means and variances of the values of  $[\delta(A) - \delta(B)] \times 10$  at different levels for the various pairs of stations are computed and the results shown in Figs 2 and 3. Values of zero or near zero for the mean suggests absence of horizontal motion at that level. Zero or near zero values of variance implies steadiness of motion between various pairs of stations at the level or absence of motion. Hence, a comparative study of the profiles of mean and variance could clearly suggest the layer of no motion. It is to be not-

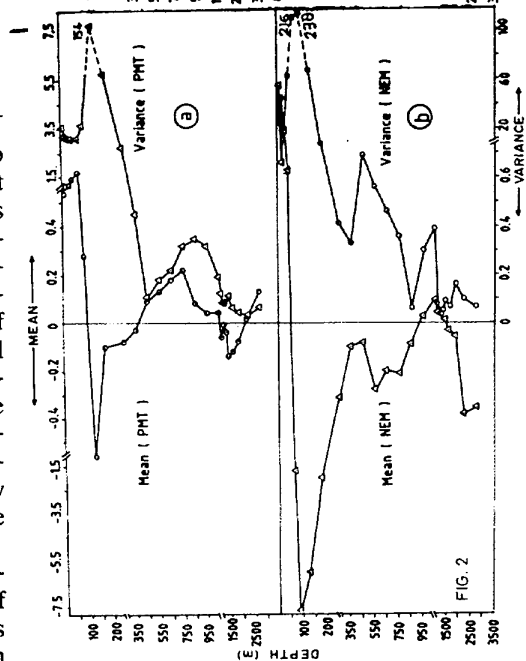


FIG. 2

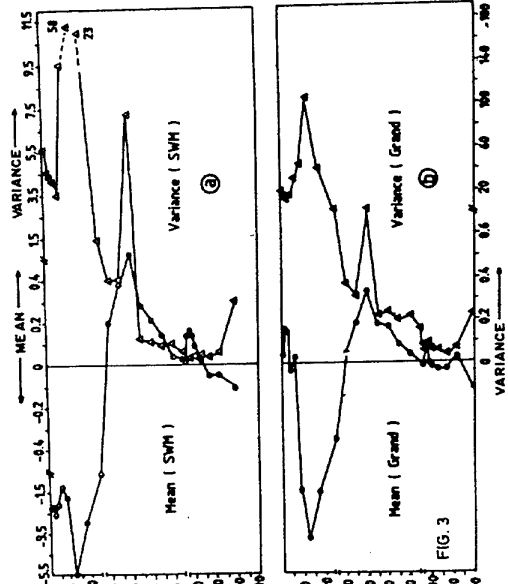


FIG. 3

Fig. 2—Vertical profiles of mean and variance of the gradient of the differential dynamic depths for northeast monsoon season (NEM) and post monsoon transition season (PMT)  
Fig. 3—Vertical profiles of mean and variance of gradient of the differential dynamic depths for southwest monsoon season and the grand mean values

ed that by taking constant alignment of station pairs in regions of steady unidirectional currents the variance estimates would reduce considerably.

From Figs 2 and 3 it is seen that there exist 2 layers of high currents with high variability in all seasons and in the mean yearly profiles; the 1st layer extending up to the bottom of the thermocline and the 2nd lower layer extending up to about 900 m with a layer of transition between 300 and 450 m. In Figs. 2(a) and 3(a), the layer 1150-2500 is of very low currents and low variability—what is plotted is variance of  $\{[\bar{\alpha}(A) - \bar{\alpha}(B)] \times 10\}$ . But in Fig. 2(b) for NEM, this layer of low variability extends only up to 1500 m. But the low number of stations for NEM is to be taken into account here. The existence of an intermediate layer with dominating horizontal flows between 1200 and 1700 m in the north Indian Ocean<sup>5</sup> has been confirmed by Varkey<sup>4</sup> who showed that this intermediate layer has larger velocities during the SWM period compared to NEM period when the Bay of Bengal experiences a net sinking above 1200 m. The velocities in this layer could perhaps go up to about  $10 \text{ cm s}^{-1}$ . Even currents of this magnitude during NEM and SWM in the layer 1200-1700 m are resolvable from Figs. 2(b) and 3(a); supporting the reliability of the method.

From the above results, it is clear that 2500 m could be considered as a layer of no motion for the north Indian Ocean, if one wants to go deeper to a

depth where the seasonal variations are ineffective. But 1100 m could be considered as a practical approximation for the layer of no motion for the Bay of Bengal or the eastern equatorial Indian Ocean. Wyrski<sup>6</sup> considered 3000 decibar as the reference level for the north Indian Ocean on a yearly basis and 1000 m on a 2 monthly basis. Again, Bennette<sup>5</sup> postulated that North Atlantic Deep Water penetrates northwards to the head of the Bay of Bengal at about 2500 m. Considering 2500 m as the upper level of this northward moving deep water, upward from 2500 to about 1700 m, vertical motions could dominate ruling out horizontal motions, perhaps, completely. Hence selection of 2500 m as the layer of no motion seems to be very accurate.

### References

- 1 Fomin L M, *The dynamic method in oceanography* (Elsevier Publishing Co., Amsterdam) 1964, 212.
- 2 Wunsch C, *Rev Geophys & Space Phys*, **16** (1978) 583.
- 3 Sverdrup H U, Johnson M W & Fleming R H, *The oceans, their physics, chemistry and general biology* (Asia Publishing House, Bombay) 1961, 1087.
- 4 Varkey M J, *Salt balance and mixing in the Bay of Bengal*, Ph D thesis, University of Kerala, 1986.
- 5 Bennette E B, *Turbulent diffusion, advection and water structure in the north Indian Ocean*, Ph D dissertation, University of Hawaii, 1970.
- 6 Wyrski K, *Oceanographic atlas of the International Indian Ocean Expedition* (National Science Foundation, Washington DC) 1971, 531.