

## ON THE VERGENCE FIELD IN THE NORTH INDIAN OCEAN

by

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### ABSTRACT

The paper presents some of the results of investigation on the divergence and convergence of the surface waters in the North Indian Ocean, for different months of the year. The divergence is computed by a graphical method from the data on surface currents.

The divergence pattern shows considerable seasonal and space variations. Several centres of strong divergence and convergence occur in the open ocean regions in the equatorial parts of the Indian Ocean throughout the year. But strong divergences and convergences also occur in nearshore regions during certain periods of the year; for example, on the east coast of India, a strong divergence occurs in the month of March. Similarly, on the Somali coast, strong divergences with central values exceeding 40 units (1 unit =  $2 \times 10^{-7} \text{ sec}^{-1}$ ) often occur.

The investigation shows that the monsoon months (June, July and August) are the months of intense divergence of surface currents in the North Indian Ocean. During this period, the central values of some of the divergences and convergences exceed 60 units. The intense divergence during the monsoon months may be ascribed to the strong monsoon winds over the area.

The divergence field indicates that along the east coast of India, upwelling may be prevalent during the period January to August while sinking may be prevalent during the remaining period of the year. This is in agreement with the earlier findings by the authors and others on upwelling on the east coast of India as deduced from temperature structure, etc. Along the west coast of India, divergence is prevalent from January to May or June. Along the Somali coast, divergence is prevalent from March to August, indicating upwelling.

### INTRODUCTION

Divergence and convergence in the sea are processes of vital importance to the physical oceanographer as well as marine biologist. Positive and negative values of vergence are called divergence and convergence respectively. They are closely related to the vertical movements of water known as upwelling and sinking. Regions of divergence are defined as those where surface waters

of the ocean flow away from each other so that waters from subsurface depths rise as a feature of upwelling (SVERDRUP, 1942). Such areas, whether at the sea coast or in the open sea, are generally productive of plankton and are important centres of fish production. Regions of convergence are areas where surface waters meet and sink. Such areas are relatively barren of plankton. A mapping of the vergence field over the North Indian Ocean for different months of the year appears to be quite necessary and important in view of the Indian Ocean Expedition.

Studies on the convergence and divergence in the Indian Ocean are quite meagre. HIDAHA (1955) derived a method to calculate the divergence of the surface drift vectors in terms of the wind stresses over the oceans and HIDAHA and OGAWA (1958) mapped the field of surface divergence based on wind stresses, for the Indian Ocean for the four seasons. But this method has a defect in that the absolute value of divergence becomes infinite at the equator and hence the divergence pattern could not be obtained at the equator by this method. Direct evaluation of the divergence from surface current vectors would be much better than wind stress method, if we can get sufficient data for surface currents. VAN DIJK (1956) and HIDEO SUDO (1960) obtained the distribution of divergence for the Indian Ocean and the Pacific Ocean respectively, directly from the current charts. DIJK's studies on divergence for the Indian Ocean pertain to the month of January only. An attempt was made by the authors (1962) to locate upwelling and sinking in the North Indian Ocean for the month of March from divergence pattern obtained from the distribution of surface currents.

#### DATA USED AND METHODS OF STUDY

The data obtained from the current charts of the Indian Ocean (H.O. Publ. No. 566) published by the U.S. Navy Hydrographic Office in 1944 and reprinted in 1950, have been used for evaluating the vergence. These charts show monthly surface currents based on the information compiled from the observations of the vessels' drifts made during the different months for all the years prior to 1935 by the co-operating observers of the Hydrographic Office. The currents are considered to be not so reliable in cases where tidal currents prevail and where winds, seas or swells are strong, etc. On these current charts are indicated the mean direction by an arrow, the resultant drift in miles per day (to the first decimal place), and the total number of current observations used in the computation in each one-degree quadrangle for the month.

Indian Ocean has been considered for the present study.

The horizontal divergence is given by

$$\nabla \cdot V_H = \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} - v \frac{\tan \Phi}{r} \quad (1)$$

where  $x$  and  $y$  are directed towards the east and north respectively and  $u$  and  $v$  are the components of the current along east and north,  $\Phi$  is the latitude of the place and  $r$  is the radius of the earth (SHERMAN, 1952). It can be shown that the term  $\frac{v \tan \Phi}{r}$  is very small in low latitudes compared to the other terms of the expression for horizontal divergence and can be neglected. Hence, the divergence is graphically evaluated using the relation

$$\nabla \cdot V_H = \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} \quad (2)$$

The method of finite differences (SAUCIER, 1955) with a grid interval of  $1^\circ$  of latitude has been used for obtaining the divergence. The  $u$  and  $v$  components of the current are first obtained from the current velocity vector in each one-degree quadrangle indicated on the current charts. The  $u$  and  $v$  fields are analysed. Fields of  $\frac{\Delta u}{\Delta x}$  and  $\frac{\Delta v}{\Delta y}$  are obtained from the  $u$  and  $v$  fields respectively, by a graphical method using an interval of  $1^\circ$  of latitude for  $\Delta x$  and  $\Delta y$ . The vergence field is finally obtained by a graphical addition of the fields of  $\frac{\Delta u}{\Delta x}$  and  $\frac{\Delta v}{\Delta y}$  (assuming that finite differences can be used in the place of partial differentials). The method differs from that of SUDO (1960) in that the vergence is obtained by a graphical method instead of by computation and a one-degree grid is used instead of the five-degree grid used by SUDO.

#### DISCUSSION OF RESULTS

The vergence fields of surface currents of the North Indian Ocean for different months of the year are mapped and shown in Figs. 1 A to L. Areas of divergence are dotted in the figures and areas of convergence are left blank. The isolines of convergence and divergence are drawn at intervals of 30 units (1 unit =  $2 \times 10^{-7} \text{ sec}^{-1}$ ). The analysis extends from equator to  $25^\circ$  north and from  $40^\circ$  east to  $100^\circ$  east. The Red Sea and the Persian Gulf are not included in the present study. The vergence field shown in the figures does not extend right up to the land boundaries. It will be representative only from a few miles off-shore.

gence centres whose central values exceed  $\pm 30$  units are termed as strong centres in the following discussion.

In the month of January, divergence prevails along the west coast of India, the east coast of India north of  $13^{\circ}\text{N}$ , the east coast of Ceylon, the northern half of Burma coast and the coast of Somaliland. The centres of strong divergence are located at  $65^{\circ}\text{E}:0.5^{\circ}\text{N}$ ,  $72.5^{\circ}\text{E}:5^{\circ}\text{N}$ ,  $74^{\circ}\text{E}:0.5^{\circ}\text{N}$ , and  $76.5^{\circ}\text{E}:5^{\circ}\text{N}$ . Strong convergence centres are located at  $50^{\circ}\text{E}:4.5^{\circ}\text{N}$ ,  $68.5^{\circ}\text{E}:2^{\circ}\text{N}$  and  $75.5^{\circ}\text{E}:3^{\circ}\text{N}$ .

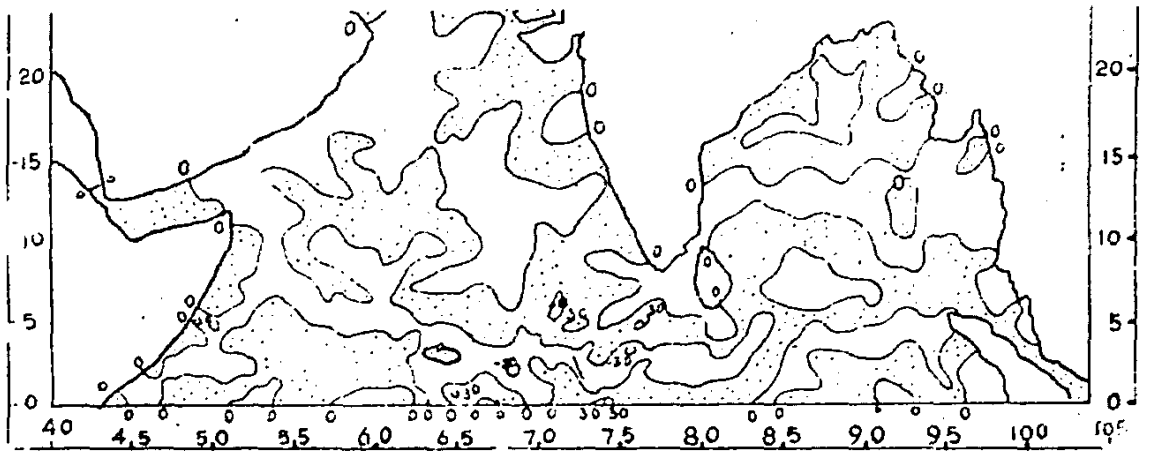
In February, there is divergence along the west coast of India, the east coast of India, the west coast of Burma, the east and north coasts of Ceylon, the Arabian coast and the Somali coast. Strong divergence centres are found at  $50^{\circ}\text{E}:5.5^{\circ}\text{N}$ ,  $56.5^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $62.5^{\circ}\text{E}:3^{\circ}\text{N}$  and  $67^{\circ}\text{E}:1.5^{\circ}\text{N}$ . A strong centre of convergence is located at  $47^{\circ}\text{E}:2.5^{\circ}\text{N}$ .

In the month of March, divergence occurs along the Somali coast, the Arabian coast, the west and east coasts of India, the Burma coast, the Thai and Malaya coasts and the east and north coasts of Ceylon. Strong centres of divergence are located at  $64^{\circ}\text{E}:1.5^{\circ}\text{N}$ ,  $71^{\circ}\text{E}:3^{\circ}\text{N}$ ,  $73.5^{\circ}\text{E}:7^{\circ}\text{N}$ ,  $80.5^{\circ}\text{E}:15.5^{\circ}\text{N}$  and  $97^{\circ}\text{E}:16.5^{\circ}\text{N}$ . There is no strong convergence centre.

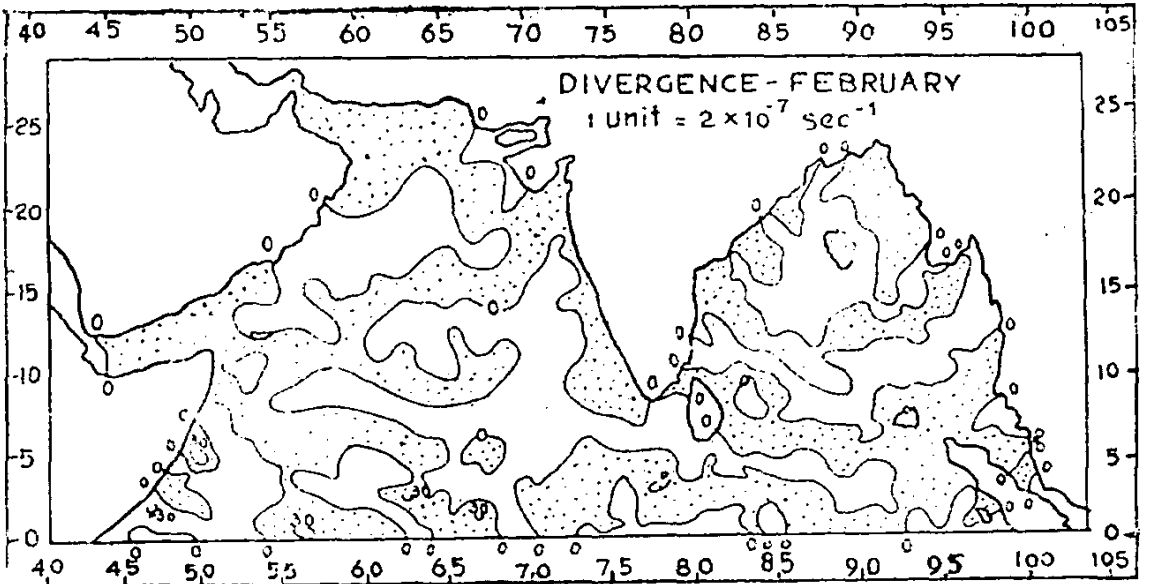
In April, divergence prevails along the major part of the west and east coasts of India, the southern part of Burma coast, the coasts of Ceylon, the Arabian coast, the coasts of Thailand and Malaya, and some areas along the Somali coast. Strong divergence centres are located at  $44^{\circ}\text{E}:0.5^{\circ}\text{N}$ ,  $51.5^{\circ}\text{E}:9.5^{\circ}\text{N}$ ,  $62.5^{\circ}\text{E}:2.5^{\circ}\text{N}$ ,  $70^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $72.5^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $75^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $83^{\circ}\text{E}:17^{\circ}\text{N}$ ,  $88.5^{\circ}\text{E}:12.5^{\circ}\text{N}$ ,  $89^{\circ}\text{E}:4^{\circ}\text{N}$ ,  $91.5^{\circ}\text{E}:4.5^{\circ}\text{N}$ ,  $92.5^{\circ}\text{E}:0^{\circ}$  and  $98^{\circ}\text{E}:0^{\circ}$ . The centres of strong convergence are at  $75^{\circ}\text{E}:0^{\circ}$ ,  $80.5^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $86.5^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $87^{\circ}\text{E}:13.5^{\circ}\text{N}$  and  $94.5^{\circ}\text{E}:0^{\circ}$ .

In May, there is divergence along the Somali coast, the Arabian coast, the west and east coasts of India, the Burma coast, the Thai and Malaya coasts and the east coast of Ceylon. The centres of strong divergence are located at  $47^{\circ}\text{E}:3^{\circ}\text{N}$ ,  $48.5^{\circ}\text{E}:5.5^{\circ}\text{N}$ ,  $67.5^{\circ}\text{E}:0.5^{\circ}\text{N}$ ,  $60^{\circ}\text{E}:18.5^{\circ}\text{N}$ ,  $72^{\circ}\text{E}:5.5^{\circ}\text{N}$ ,  $72.5^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $75^{\circ}\text{E}:10^{\circ}\text{N}$  and  $75.5^{\circ}\text{E}:2^{\circ}\text{N}$ . Strong convergence centres are situated at  $46.5^{\circ}\text{E}:1.5^{\circ}\text{N}$ ,  $48.5^{\circ}\text{E}:3.5^{\circ}\text{N}$ ,  $61^{\circ}\text{E}:18.5^{\circ}\text{N}$ ,  $71.5^{\circ}\text{E}:0^{\circ}$ ,  $74.5^{\circ}\text{E}:4^{\circ}\text{N}$ ,  $81^{\circ}\text{E}:0.5^{\circ}\text{N}$ ,  $82^{\circ}\text{E}:11.5^{\circ}\text{N}$ ,  $83.5^{\circ}\text{E}:1^{\circ}\text{N}$ ,  $87^{\circ}\text{E}:0.5^{\circ}\text{N}$  and  $89.5^{\circ}\text{E}:1^{\circ}\text{N}$ .

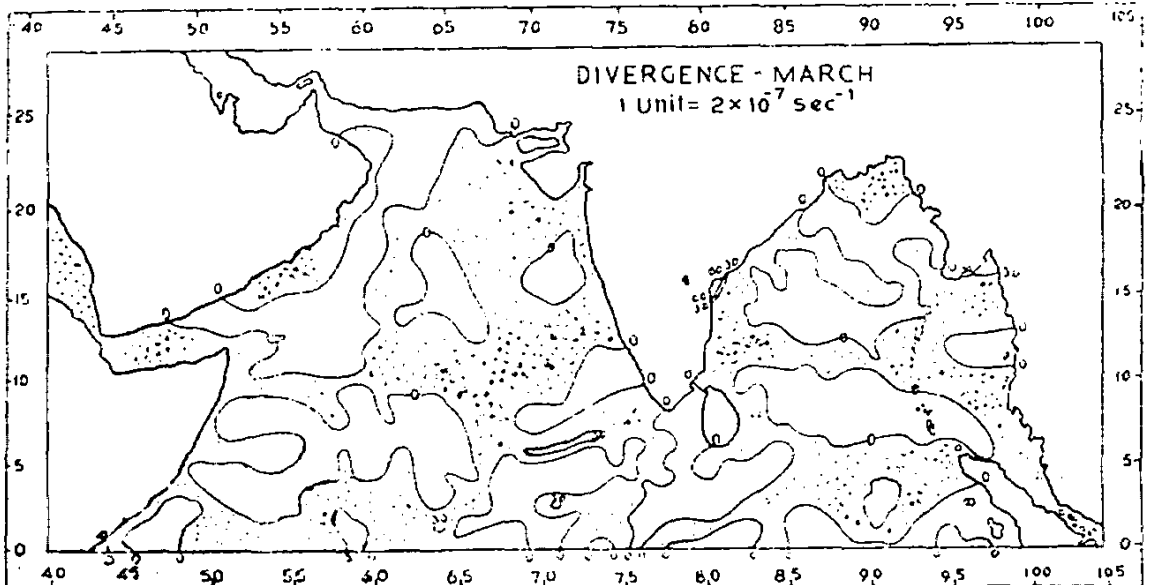
In the month of June, divergence prevails along the Somali coast, the Arabian coast, the west and east coasts of India, and the west and the south-



A



B



C

Fig. 1. A,B,C—Vergence fields of surface currents in the North Indian Ocean for the months of January, February and March.

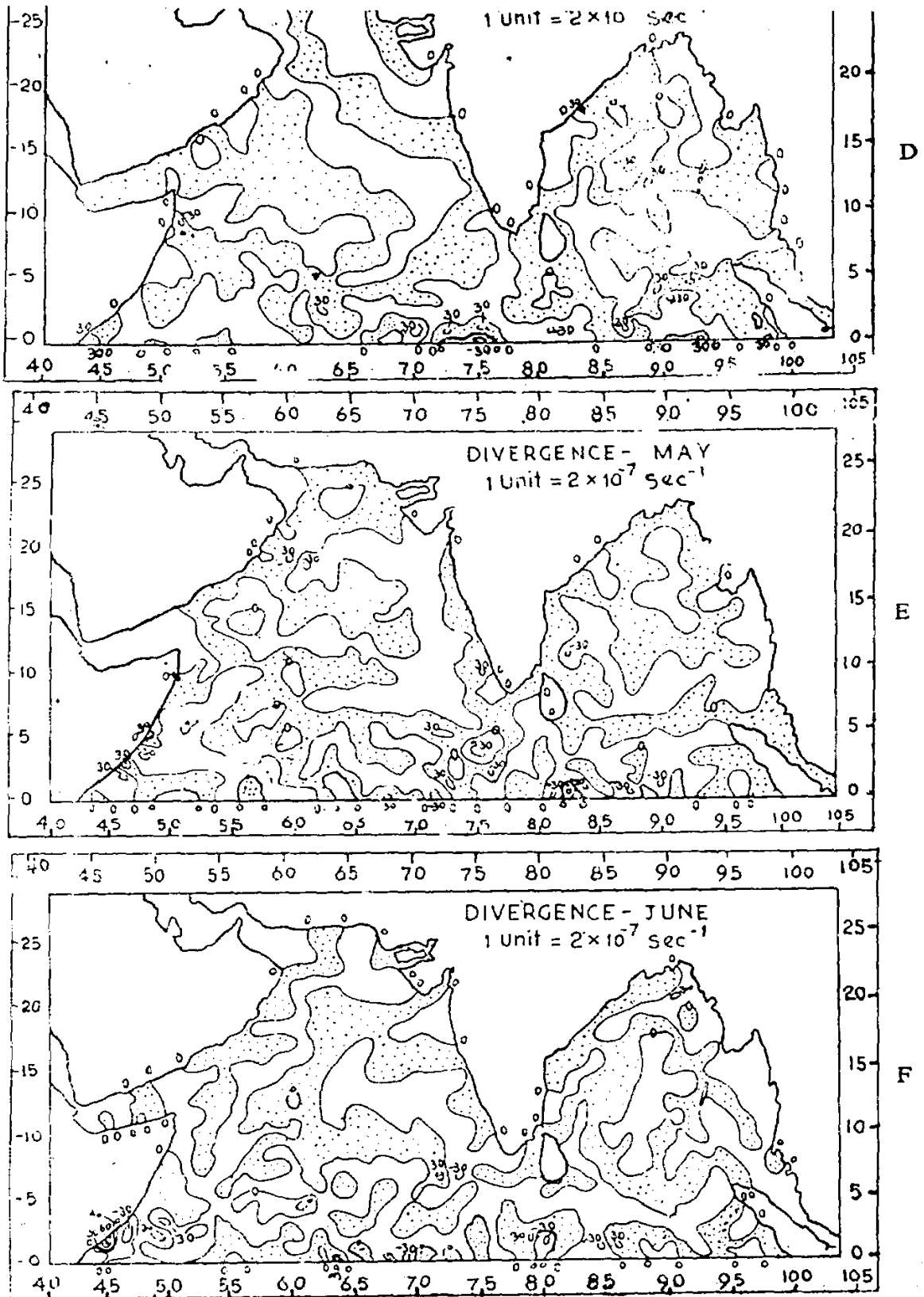
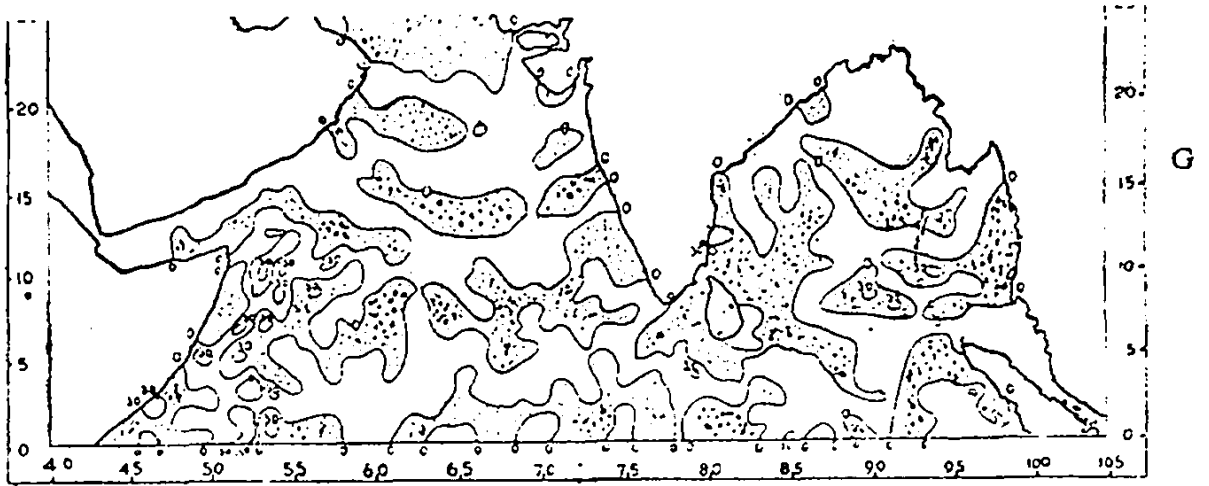
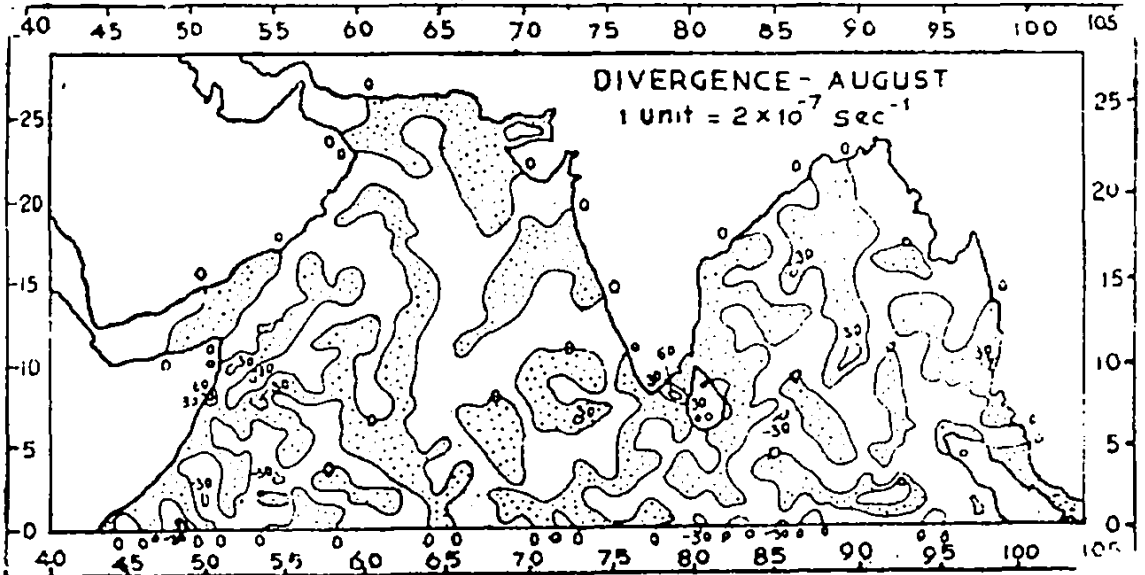


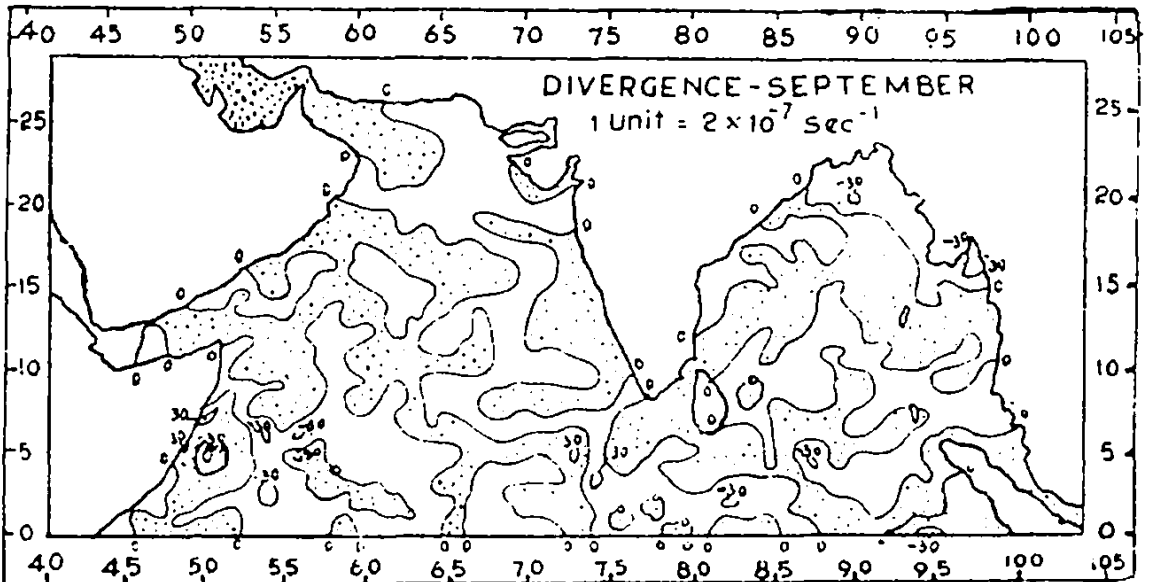
Fig. 1. D,E,F—Vergence fields of surface currents in the North Indian Ocean for the months of April, May and June.



G

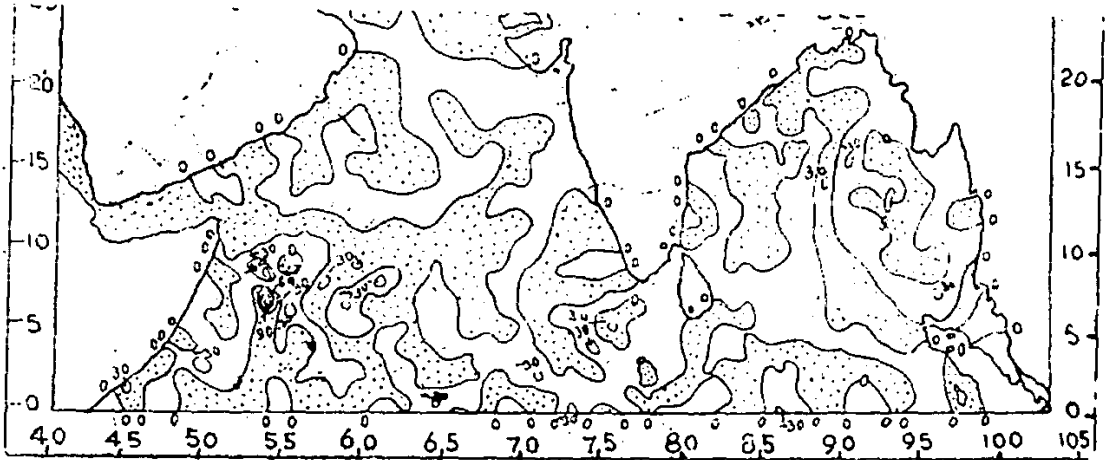


H

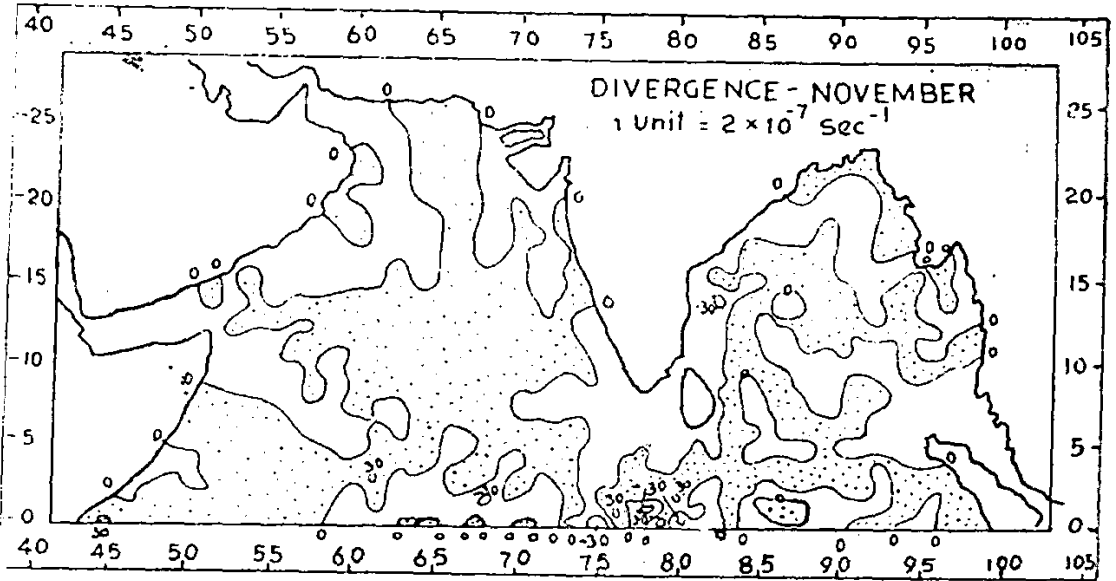


I

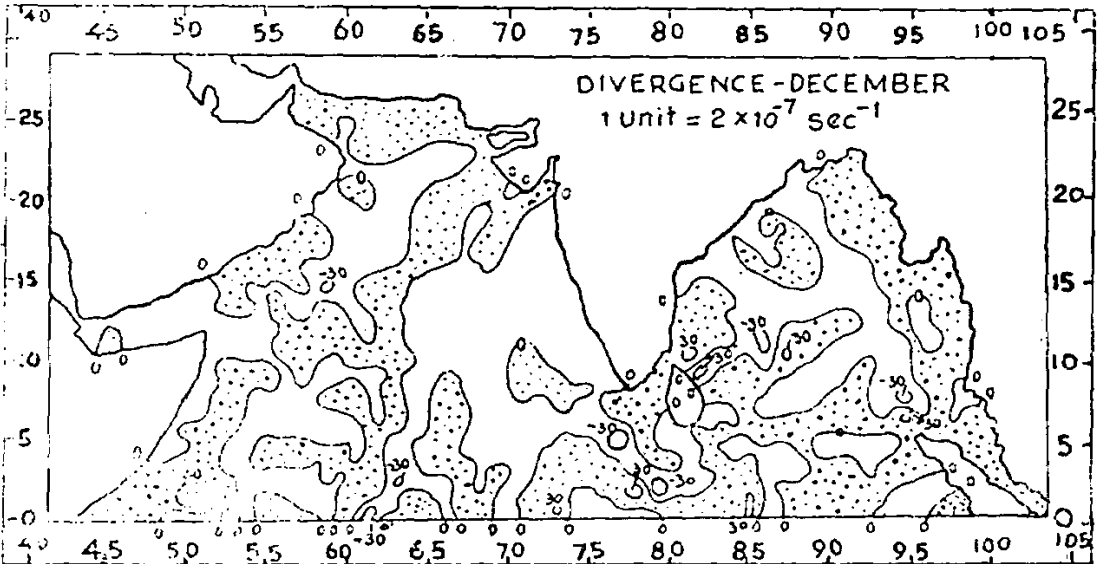
Fig. 1. G,H,I—Vergence fields of surface currents in the North Indian Ocean for the months of July, August and September.



J



K



L

Fig. 1. J,K,L—Vergence fields of surface currents in the North Indian Ocean for the months of October, November and December.



71.5°E:0.5°N, 79°E:1.5°N and 80.5°E:1°N. Strong convergence centres are located at 47°E:2.5°N, 50°E:3°N, 52°E:2°N, 69°E:0°, 73.5°E:6.5°N, 80°E:1.5°N, 84.5°E:0.5°N and 90.5°E:20°N.

In July, divergence is prevalent along the Somali coast, the southern half of west and east coasts of India, the west and the north-east coasts of Ceylon and southern half of Burma coast. Strong divergence centres are located at 46.5°E:2.5°N, 51.5°E:5°N, 53°E:1.5°N, 53°E:10°N, 53.5°E:7.5°N, 56.5°E:9°N, 80°E:11°N, 90°E:8.5°N, 91.5°E:8°N, and 93.5°E:10°N. Strong convergence occurs at 49.5°E:5°N, 51.5°E:1.0°N, 51.5°E:7°N, 53.5°E:3°N, 54°E:9°N, 54°E:10°N, 57°E:10.5°N, 79°E:4°N, and 84.5°E:0.5°N.

In the month of August, divergence occurs along the Somali coast, the central part of the west coast of India, major part of the east coast of India, the Thai and Malay coasts and the west and north coasts of Ceylon. The centres of strong divergence are located at 50.5°E:8.5°N, 52°E:10°N, 53.5°E:8°N, 73°E:7°N, 79°E:8°N, 86°E:15°N, 90°E:11°N, and 98°E:10°N. Strong convergence centres are at 48.5°E:0°, 49.5°E:2°N, 53°E:9.5°N, 54.5°E:3°N, 80.5°E:0.5°N, 85.5°E:0°, and 85.5°E:7°N.

In September, divergence prevails along the west coast of India, the west coast of Ceylon, the Arabian coast and the central part of the Somali coast. Convergence occurs along the east coast of India and the Burma coast. The centres of strong divergence appear at 49°E:5.0°, 55°E:7°N, 55.5°E:5°N, and 72.5°E:5°N. Strong convergence occurs at 50°E:5°N, 54°E:2.5°N, 54°E:6°N, 56°E:6.5°N, 74°E:3.5°N, 82.5°E:2°N, 87.5°E:4°N, 89.5°E:19.5°N, 95°E:0° and 97°E:16°N.

In the month of October, divergence occurs along the Arabian coast and the Somali coast. Convergence prevails along the west and east coasts of India, the Burma coast and the coasts of Ceylon. The centres of strong divergence are located at 45°E:1.5°N, 54°E:7°N, 58°E:8°N, 60°E:9°N, 75.5°E:5°N and 89°E:13.5°N. Strong convergence centres appear at 50°E:3°N, 54°E:8.5°N, 55.5°E:6.5°N, 59°E:6.5°N, 61°E:8°N, 64.5°E:0.5°N, 71°E:2°N, 73°E:0°, 74.5°E:4°N, 86.5°E:0°, 90°E:15°N, and 96.5°E:7°N.

In November, divergence occurs along the northern half of Burma coast and the central part of the west coast of India. Convergence prevails along the east and west coasts of India, the Arabian coast, the coasts of Ceylon, the Thai and Malay coasts and the southern half of Burma coast. The centres of

1°N, 80°E:0.5°N and 82.5°E:14°N.

In December, convergence prevails along the west and east coasts of India, the south coast of Ceylon, the Arabian coast and the northern half of Somali coast. Divergence occurs off the southern half of Somali coast, the central part of Arabian coast, the Madras coast, the Burma coast, the Thai and Malay coasts and the west and north coasts of Ceylon. Strong divergence centres appear at 50.5°E:1.5°N, 73°E:0.5°N, 78°E:2°N, 81°E:10.5°N, 87°E:10.5°N and 94.5°E:7°N. The centres of strong convergence are located at 58.5°E:14.5°N, 61.5°E:0.5°N, 63°E:2.5°N, 77°E:5.5°N, 79°E:2.5°N, 81.5°E:9.5°N, 86°E:11.5°N, and 94.5°E: 8°N.

Thus, it is found that the equatorial regions of the North Indian Ocean are the areas of strong vergence centres throughout the year. The number of strong vergence centres in the equatorial regions (0 to 5°N) exceeds the number north of 5°N almost throughout the year except the monsoon months of July and August. The vergence field is weak in the months of January, February and March (the number of strong centres is quite small during this period). It gets stronger from April. The monsoon months (June, July and August) are the months of intense vergence of surface currents in the North Indian Ocean. From September onwards, the strength of the vergence field gradually decreases. The intense divergence during the monsoon months may be ascribed to the strong winds over the area during the period of the south-west monsoon. Strong divergences and convergences occur along the Somali coast almost throughout the year.

#### *Relation of the distribution of vergence to the pressure field*

The pressure field over the North Indian Ocean shows that there are practically no closed circulations (highs and lows) in the atmosphere over the North Indian Ocean in any month of the year (*Climatological Atlas for Airmen*, 1943, published by the India Meteorological Department). However, some ridges and troughs in the pressure field appear over the area. As the net transport of sea water by the wind is at right angles and to the right in the Northern Hemisphere, a trough in the pressure field must cause divergence of the surface currents and a ridge must cause convergence. A study of the vergence field in relation to the troughs and ridges over the North Indian Ocean in different months shows that, in general, divergence occurs in the region of troughs and convergence in the region of ridges. Thus, in the month of January, the pressure field indicates a ridge near the southern part of the east coast of India and a trough near the west coast of India. The vergence map for January

vergence located at  $88.5^{\circ}\text{E}:12.5^{\circ}\text{N}$  lies in the region of the high pressure field. In September, the ridge line in the pressure field in the Arabian sea roughly coincides with a convergence zone on the vergence map.

*Relation of vergence field along a coast to the prevailing winds  
or coastal currents*

The vergence maps show that along the east coast of India, divergence prevails from January to August while convergence is predominant for the remaining period of the year. The periods of divergence and convergence coincide roughly with the periods of flow of northerly current and southerly current respectively. The importance of coastal currents as factors in inducing upwelling and sinking on the east coast of India was discussed by VARADACHARI (1961). Along the Burma coast, convergence prevails from June to October. This is also roughly the period of onshore winds on the Burma coast. Along the west coast of India, divergence prevails from January to June. The period of divergence coincides roughly with the flow of southerly current along the coast.

*Comparison with the divergence field computed from the  
distribution of wind stresses, etc.*

HIDAKA and OGAWA (1958) computed the divergence of surface drift vectors for the Indian Ocean using the distribution of wind stresses. These values depend on the magnitude of the coefficient of eddy viscosity which is rather uncertain. Moreover, the divergence was computed by them only for the four seasons of the year and for the year as a whole instead of every month. Further, the equatorial regions had to be left out by them because their formula does not permit a calculation of divergence near the equatorial regions as it leads to infinite divergence because the coriolis parameter is small there. They used a five-degree latitude-longitude grid for computing divergence while the authors used one-degree grid for their graphical evaluation of vergence. In view of these considerations a close comparison of the present results with those of HIDAKA and OGAWA would not be possible. HIDAKA and OGAWA's tables show that the strongest divergences and convergences in the North Indian Ocean occur in summer (July). This agrees very well with the results obtained by the authors. HIDAKA and OGAWA's results show a strong divergence at  $55^{\circ}\text{E}:10^{\circ}\text{N}$  in summer. The vergence map of the authors for July shows two strong divergences at  $53^{\circ}\text{E}:10^{\circ}\text{N}$  and  $56.5^{\circ}\text{E}:9^{\circ}\text{N}$ . A similar agreement between the results obtained by the authors and those of HIDAKA and OGAWA is found for the winter, spring and autumn months also.

his map shows a general agreement with regard to the sign of divergence in different areas. DIJK's map shows equatorial regions and the Somali coast to be areas of relatively strong divergence which is in agreement with the results obtained by the authors.

The magnitude of maximum divergence shown on DIJK's map is

$$\frac{6(0.125 \text{ n.m})}{(222\text{km} \times 24\text{hrs.})}$$

which is equal to  $6 \times 10^{-8} \text{ sec}^{-1}$ . The values of maximum vergence shown in the tables of HIDAOKA and OGAWA for the Indian Ocean are around  $10^{-6} \text{ sec}^{-1}$  and the maximum values of SUDO (1960) for the Pacific Ocean lie around  $10^{-6} \text{ sec}^{-1}$ . The values of strong vergence in the present investigation lie around  $10^{-5} \text{ sec}^{-1}$ . Both HIDAOKA and SUDO used five-degree latitude-longitude quadrangles for calculating vergence whereas the authors used one-degree latitude for  $dx$  and  $dy$  in their graphical evaluation of divergence. The lower values for vergence as obtained by HIDAOKA and OGAWA using wind stresses and by SUDO from a direct calculation from current charts can be easily explained. The large grid interval used by them is bound to give lower values

for vergence. In view of the fact that finite differences  $\frac{\Delta u}{\Delta x}$  and  $\frac{\Delta v}{\Delta y}$  are used

in the place of partial differentials  $\frac{\delta u}{\delta x}$  and  $\frac{\delta v}{\delta y}$  in evaluating vergence, the

authors feel that  $\Delta x$  and  $\Delta y$  should be as small as possible and hence they choose one-degree latitude for  $\Delta x$  and  $\Delta y$ . There is not much justification for choosing a five-degree latitude or longitude interval for  $\Delta x$  and  $\Delta y$  although certain irregularities are smoothed out that way. It is felt that in the analysis of  $u$  and  $v$  fields most of the irregularities are smoothed out and the graphical method used by the authors may be a little better than direct calculation. The very low values of DIJK cannot be easily explained.

#### SUMMARY AND CONCLUSIONS

The vergence field in the North Indian Ocean has considerable seasonal and space variations. Several strong divergences and convergences occur in the open ocean regions in the equatorial parts of the North Indian Ocean throughout the year. But strong vergences also occur in nearshore regions during certain periods of the year ; for example, on the east coast of India a strong divergence with central values exceeding 60 units occurs in the month of March. Similarly, off the Somali coast strong divergences and convergences with central values exceeding 40 units often occur. The high value off the east coast

16.5°N in the month of March and the strong divergence and convergence shown at 54°E:7°N and 54°E:8.5°N respectively in the vergence map for October have also to be taken with some caution as they depend on inadequate observations in some of the latitude-longitude quadrangles in the respective areas.

The vergence field is weak in the months of January, February and March. It gets strong from April onwards. The monsoon months (June, July and August) are the months of intense vergence of surface currents in the North Indian Ocean. From September to December, the vergence field is less strong than that in the peak period of the south-west monsoon. The intense vergence during the south-west monsoon period may be ascribed to the strong monsoon winds over the area. In July and August the number of strong vergence centres north of 5°N exceeds the number in the equatorial regions (0 to 5°N) while it is generally the other way during the remaining part of the year.

The divergence maps indicate that along the east coast of India, divergence and consequently upwelling may prevail during the period January to August while convergence and consequently sinking may prevail during the remaining period of the year. This is in agreement with the earlier findings by LA FOND (1957) and VARADACHARI (1956 and 1958) on upwelling and sinking on the east coast of India as deduced from thermal structure, density, transparency, etc. of the coastal waters on the east coast of India. The vergence map shows that divergence is predominant along the west coast of India from January to June. Along the Somali coast, divergence is predominant from March to August.

A study of the vergence field in relation to the troughs and ridges in the pressure field over the North Indian Ocean in different months shows that in general divergence occurs in the region of troughs and convergence in the region of ridges.

The order of magnitude of the vergence of the surface waters of the North Indian Ocean as evaluated from the current charts is  $10^{-7} \text{ sec}^{-1}$  and the extreme values are of the order of  $10^{-5} \text{ sec}^{-1}$ .

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