The Mean Wind Structure over Bahrein and Aden in 1962[1]

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ABSTRACT

The mean upper wind structure over Bahrein and Aden in 1962 is studied. Patterns of the zonal and meridional wind speed components are presented. Eddy and advective fluxes of the momentum are calculated and mean annual height profiles drawn for both stations. The transport of momentum by synoptic scale eddies is more important at Bahrein than at Aden. Transport of momentum by the local mean meridional wind is larger in magnitude and fluctuates in an irregular way from month to month at both stations. The vertical integral of the momentum suggests export of relative momentum from the Bahrein-Aden sector in winter and import in summer. These conclusions are supported by 1963 data from the Ahmadabad-Madras sector. In the belt of latitude considered the winter surface winds have an easterly component and gain momentum from the earth while the summer surface winds have a westerly component and lose momentum to the earth. The results of the short period analysis for the sectors studied suggest broad agreement with the synoptic climatology of the region.

1. Introduction

Our knowledge of the structure of the wind in the troposphere and low stratosphere of the Middle East remains incomplete due to the sparseness of upper air reporting stations in the area. This is especially true over the Arabian peninsula. However, the upper air reporting stations at Bahrein (26°16′N, 50°37′E) and Aden (12°50′N, 45°02′E) which are operated by the United Kingdom Meteorological Office fill a big gap in the widely spaced network. The data provide a useful source for the study of the wind field at various pressure levels for each month of the year for two important localities within the tropics. The observations analyzed in this study consisted of the daily components of the wind for the surface, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, 100, 80 and 60 mb for 0000 and 1200 GMT for each month of the year 1962 for Bahrein and Aden. The daily values of the meridional and zonal wind components and the mean monthly values for each of the two reporting hours had been tabulated by electronic computer and these were available for the calculation of profiles of the meridional and zonal wind and of the eddy and advective fluxes of momentum for each month for both stations.

Ninety per cent of the observations reached at least 200 mb. Above 100 mb the number of observations decreased to 50 per cent or less of the maximum possible. Since Bahrein and Aden are separated by only 5°35′ of longitude it was conveniently approximated that both stations lie along the same meridian for the purpose of representing the variation of wind and momentum with latitude within this sector of Arabia.

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2. Mean zonal wind

Bahrein is located at the approximate latitude at which the subtropical jet stream reaches its maximum southward limit in January. It also lies within the influence of the summer upper easterly wind belt. Fig. 1 shows the isotach pattern of the mean westerly wind as a function of height throughout the year for this sta-

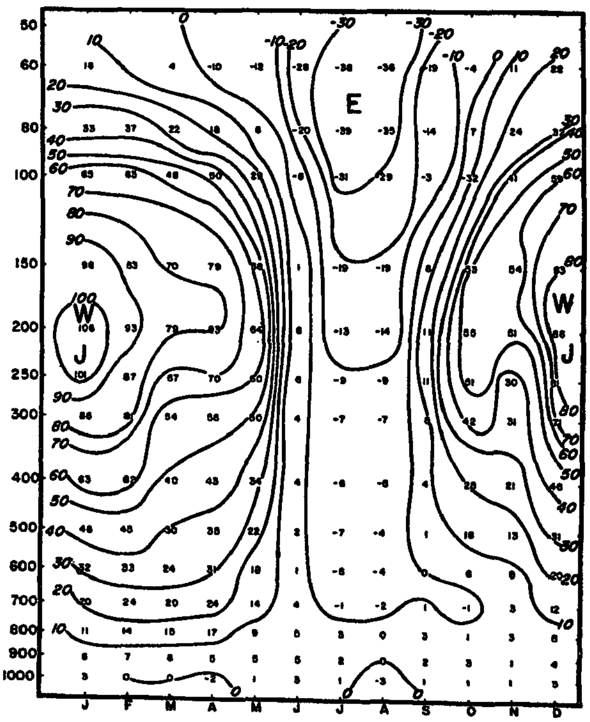

FIG. 1. Mean zonal wind speed at Bahrein in 1962 (kt).

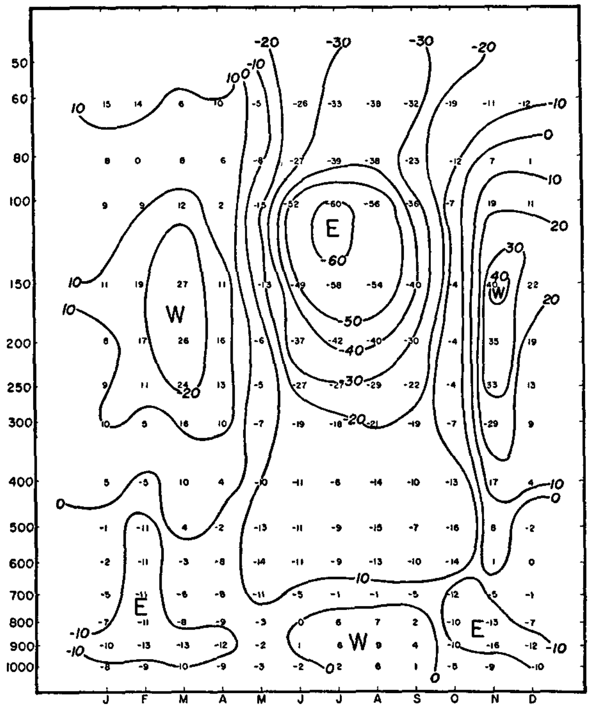

Fig. 2. Mean zonal wind speed at Aden in 1962 (kt).

tion. It is noted that the westerly subtropical jet stream reaches a maximum of over 100 kt at 200 mb in the winter months. During the winter period westerlies extend throughout the whole of the troposphere and lower stratosphere. In summer, easterlies extend upward from 700 mb reaching a maximum in July and August at or above 60 mb. There is a sharp decrease in the mean zonal component of the westerly jet between May and June and a rapid increase between September and October. The abruptness of the transition between premonsoon and summer monsoon conditions over the Indian subcontinent and surrounding oceans has been described by Raman and Dixit (1963) and other authors.

Fig. 2 shows the mean zonal component of the wind for Aden for 1962. The mean zonal wind structure reflects to some extent the general pattern observed at Bahrein but there are important differences. The upper tropospheric westerly is very much weaker than at Bahrein and the maximum isotach is only 20 kt. The summer easterly wind has reached jet stream intensity at this latitude with the core at about 125 mb, somewhat lower than at Bahrein. There is also a change in the lower troposphere where easterly winds exist from the surface to at least 600 mb in winter, whereas there is a transition to a westerly regime below 700 mb in summer.

3. Mean meridional wind

Several workers (Palmén and Vuorela, 1963; Tucker, 1959; and others) have integrated the meridional component of the wind around parallels of latitude throughout the vertical extent of the atmosphere and shown that a Hadley cell circulation exists within the tropics. The Hadley cell is usually described as a mean circulation in the vertical meridional plane extending to about 30 deg latitude on either side of the equator. This mean circulation has been averaged, mainly in the Northern Hemisphere, over time periods ranging from a day to several years. Such cells show upward vertical motion in the vicinity of the equator, a southerly mean meridional flow in the upper troposphere, downward vertical motion within the subtropics and a returning northerly mean meridional flow in the lower troposphere. The quantitative derived circulation is supported by the existence of the equatorial rain belts and subtropical deserts.

The time-averaged meridional component of the wind at single stations does not necessarily imply a Hadley cell type circulation. For example, there might on a given day, or during a period of some days, be an upper-level anticyclone to the east of the station overlying a low-level cyclone. Such a vertical distribution of the pressure field would create a meridional circulation in the Hadley sense, but it would not contribute to the mean meridional circulation when averaged around the globe. However, it is unlikely that such pressure distributions would remain for a period as long as a month. Thus, the mean meridional wind averaged over a month at single stations may well contribute to the Hadley cell circulation. The mean meridional structure at Bahrein and Aden may be regarded in this light.

Fig. 3 shows the mean meridional wind structure over

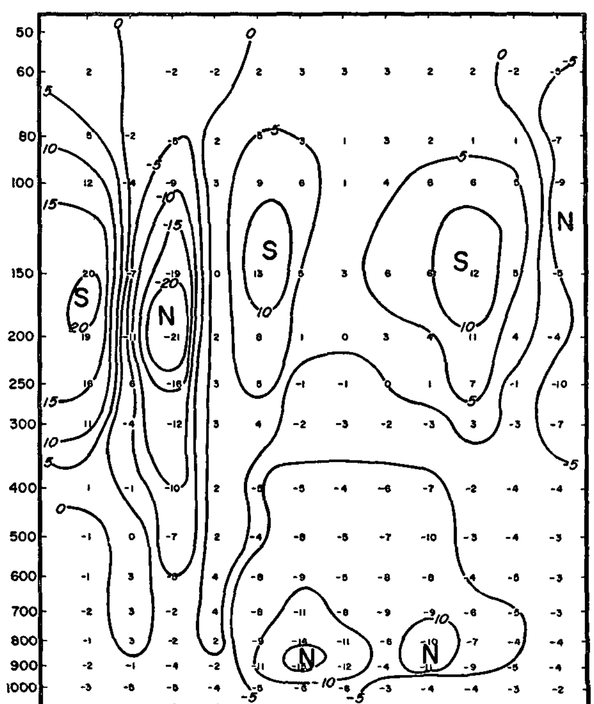

Fig. 3. Mean meridional wind speed at Bahrein in 1962 (kt).

Bahrein in 1962. From May to November a definite meridional circulation exists. During the remaining months considerable variations occur. Thus, in January, there is a light northerly component up to 400 mb which is overlain by a strong southerly component with a maximum at about 175 mb. In February and March the meridional wind in the upper troposphere and lower stratosphere is northerly. In March and December it is northerly throughout the whole column up to 60 mb. The meridional wind structure at Aden shown in Fig. 4 exhibits a toroidal (Hadley cell) regime. At Aden the maximum speeds of the low-level northerly branch are found at 600 mb as compared to Bahrein where the maximum low-level northerlies occur at about 850 mb. Maximum southerlies occur at about the same levels as at Bahrein. Below 900 mb, southerly components blow throughout the year at Aden and these extend to about 850 mb in summer. The upward extension of the surface layer westerlies is accompanied by an upward extension of the levels of the overlying low tropospheric northerlies. In March and December northerly components blow at Aden at all levels and no meridional cell circulation appears for that year.

4. Meridional fluxes at single stations

Priestley (1949) undertook an investigation of the meridional flux of heat, water vapor and momentum for Larkhill on Salisbury Plain in southwest England for the years 1946 and 1947. His purpose was to draw attention to the method and to appeal for a global investigation. Since that time research into the general circulation has advanced to a state where global projects have been undertaken on a large scale. Among those responsible are Mintz (1951), Palmén (1951), Starr (1951), Starr and White (1952a, b), Chiu and Crutcher (1965), and many others. The quantities originally calculated for one or two isolated stations have now been integrated around parallels of latitude and with height on a hemispheric or global scale. Nevertheless, as Priestley (1949) rightly remarked, global projects are too formidable for one or two individuals to undertake. However, useful knowledge can still be extracted from investigations into the quantities which prevail at one or two stations from which accurate upper air observations can be obtained. Consequently, there remains a need to make individual analyses of upper air circulations.

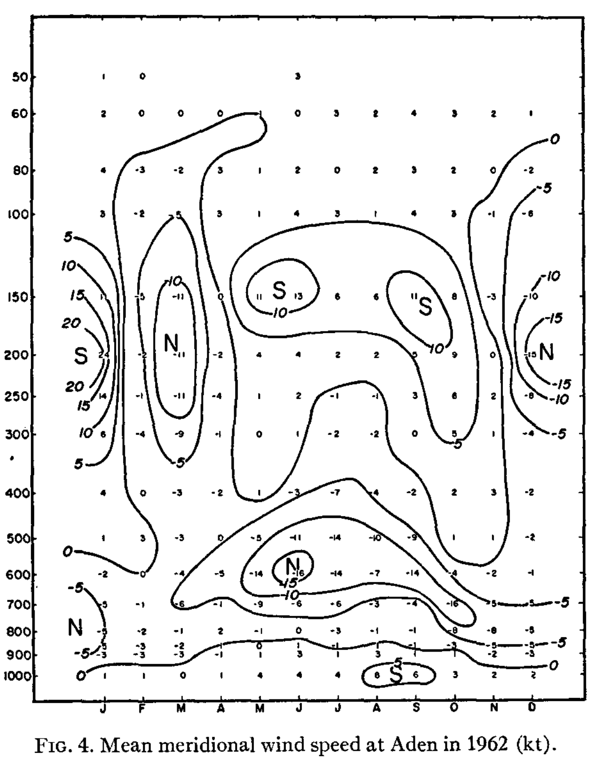

FIG. 4. Mean meridional wind speed at Aden in 1962 (kt).

5. Eddy flux of momentum

The study of the transport of the angular momentum of the atmosphere can be carried out by the use of the perturbation relations. For example, the absolute angular momentum of the air may be written

$$m = a\cos\phi(u + \Omega a\cos\phi), \tag{1}$$

where a is the radius of the earth, ϕ the latitude, Ω the angular velocity of the earth's rotation and u the velocity of the wind along a parallel of latitude measured positively towards the east. The term $au\cos\phi$ is the relative momentum while the transport of relative momentum along a meridian, positive toward the pole, and negative toward the equator, may be expressed by $uva\cos\phi$ in the Northern Hemisphere.

Now the instantaneous velocities u, v along the x and y axes, respectively, may be expressed in the form

$$\left.\begin{aligned} u &= \bar{u} + u' \\ v &= \bar{v} + v' \end{aligned}\right\}, \tag{2}$$

where the overbar represents the time average over a month, and the prime notation signifies the variation of each individual observation from the mean value. Then the sum of the individual values of the transport of the relative momentum is given by the expression

$$\Sigma uva\cos\phi = \Sigma(\bar{u}\bar{v} + u'v')a\cos\phi, \tag{3}$$

and the average total monthly transport by the relation

$$\overline{uv} = \bar{u}\bar{v} + \overline{u'v'}. \tag{4}$$

The term on the left hand side of (4) represents the flux of the relative momentum at some selected level or within a chosen layer of the atmosphere expressed in $cm^2\ sec^{-2}$ or kt^2. The first term on the right hand side represents the northward flux of zonal momentum by the local mean meridional wind while the second term on the right hand side represents the local eddy flux of zonal momentum.

If (4) is integrated throughout the vertical extent of the atmosphere and p_0 is the surface barometric pressure, the term $\int_{p_0}^{p} \overline{uv}dp$ expresses the flux of relative momentum in gm sec^{-2}. The latter units may also be written as dyn cm^{-1} in which units the vertical integral of the Reynolds stress is expressed.

The flux of relative momentum was calculated for Bahrein and Aden for each month of the year 1962 for the levels listed in the introductory paragraph. Then the eddy flux was found from (4). Fig. 5 shows the eddy flux of momentum averaged for the six 2-monthly periods of 1962 for Bahrein. A cell of poleward flux which is associated with eddies of the period of several days in the subtropical jet stream (Fig. 1), is found at about 150 mb in January and February and at about 250 mb in November and December. The flux in the lower troposphere is directed toward the equator at all times of the year. There is also equatorward flux in May-June between 150 and 200 mb, which is associated with the transition from westerlies to easterlies (Fig. 1). Poleward flux occurs at all periods from 500 to 250 mb. The pattern of the eddy flux of momentum at Aden shown in Fig. 6 is very weak. In contrast to Bahrein the flux at low levels is toward the pole. Maximum flux is toward the equator in the low stratosphere in March-April and November-December. This flux is associated with high level northwesterly winds which occurred during the latter months. Starr and White (1952b) reported a tendency for equatorward transport at high levels at 13N. In Fig. 7 the patterns have been averaged to give a mean annual profile with height. The level of zero transport at Bahrein is about 550 mb and the transport is equatorward below this level and poleward above it. Maximum flux in the mean annual profile is 95 kt^2 at 300

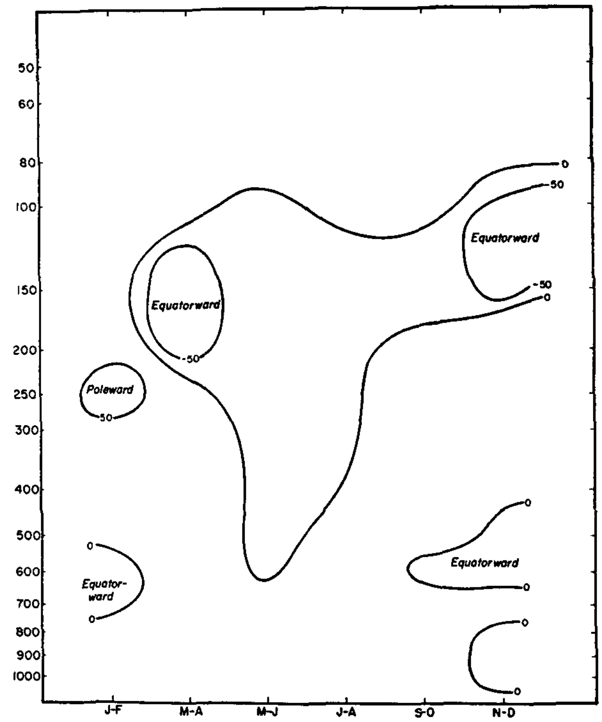

FIG. 6. Eddy flux of momentum at Aden in 1962 (kt^2).

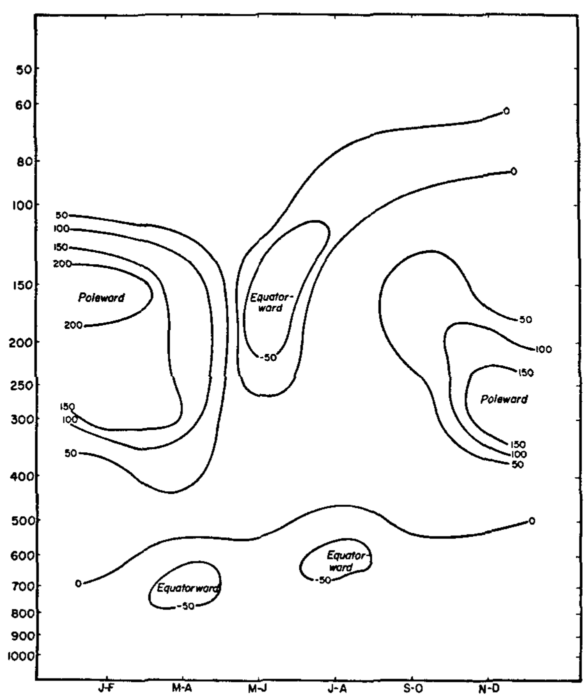

FIG. 5. Eddy flux of momentum at Bahrein in 1962 (kt^2).

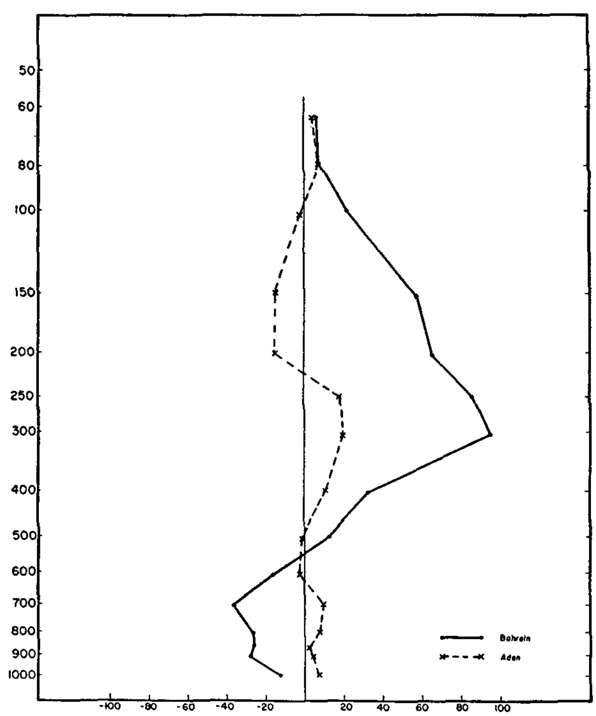

FIG. 7. Mean annual profile of the eddy flux of momentum at Bahrein and Aden in 1962 (kt^2). Positive is poleward.

mb. Conversion to cgs units gives a maximum mean value of 2.5×10^5 cm^2 sec^{-2}. Starr and White (1952a) found a mean winter value of poleward eddy flux of momentum of about 6.2×10^5 cm^2 sec^{-2} at 30N and about 250 mb when averaged around the globe during one year. Tucker (1964) suggests a maximum poleward flux of about 3.8×10^5 cm^2 sec^{-2} at 25N and 300 mb for the winter months averaged over a 2-yr period. The maximum flux at Bahrein, averaged over a month in 1962, was in March at 200 mb with a value of 13.2×10^5 cm^2 sec^{-2}.

The mean annual profile of the eddy flux at Aden is different from that at Bahrein as shown in Fig. 7. The Aden profile shows a poleward flux up to about 225 mb and only a narrow belt of equatorward flux above. The magnitude of the flux is much less than at Bahrein.

6. Advective momentum

The advective momentum flux given by the term $\bar{u}\bar{v}$ was also computed. The month to month patterns are not reproduced here. They are more variable and greater in magnitude when averaged over a month than the eddy momentum flux and closely controlled by the variations in the mean meridional winds (Figs. 3 and

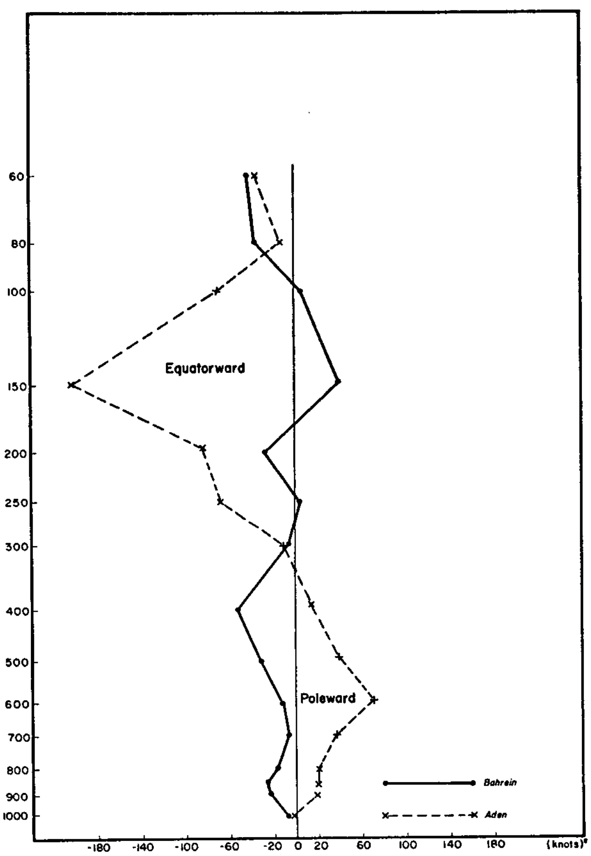

FIG. 8. Mean annual profile of the advective flux of momentum at Bahrein and Aden in 1962 (kt²).

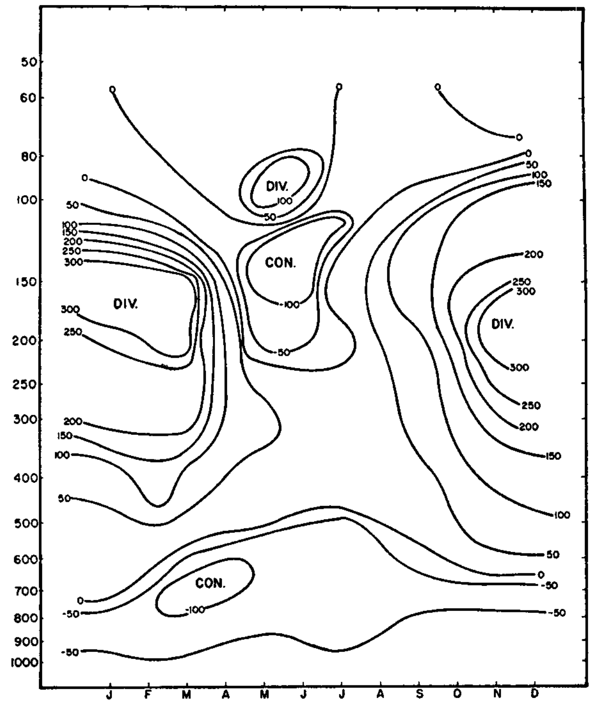

FIG. 9. Divergence of the eddy flux of momentum within the Bahrein-Aden sector in 1962 (10^{-5} cm sec^{-2}).

4). Fig. 8 shows the mean annual profiles of advective momentum for Bahrein and Aden for 1962. The profiles below 300 mb show equatorward advection at Bahrein and poleward advection at Aden. The advective flux reaches a maximum toward the equator at Aden at 150 mb. This is brought about by the combination of northwest winds in the spring and winter months and by southeast winds in the summer months of 1962. In contrast to Aden there is relatively little advection at Bahrein.

7. Divergence of momentum

Fig. 9 shows the divergence of the eddy flux of momentum for the Bahrein-Aden sector for 1962. Convergence of flux occurs in the lower troposphere. Centers of maximum divergence occur at about 150 mb in winter. In summer weak divergence overlies the convergence from 500 to 200 mb and a center of convergence is found at about 150 mb. There is some evidence of upward flux in winter whereas in summer the upward flux appears weaker. In 1962 there appears to be some downward flux in May and June in the upper troposphere. The mean annual profile of the divergence of eddy and advective momentum is given in Fig. 10. It is seen that there is low-level convergence and high-level divergence of both fluxes. Such a distribution would give a mean annual upward vertical transport of both fluxes. A study of the mean meridional wind patterns in Figs. 3 and 4 shows that the advection of the Earth's momentum within the sector would also give rise to a mean annual upward transport. However, these conclusions may be limited by the neglect of variations of the wind with longitude due to the fact that the two stations do not lie exactly along the same meridian.

8. The vertical integral of the momentum flux

The patterns of the momentum fluxes illustrated in Figs. 5–10 are based on values computed for selected levels. However, if the vertical integrals of the fluxes throughout the atmospheric column at Aden and Bahrein are subtracted from one another the difference will give the total import or export of momentum within the sector. If this difference is divided by the meridional distance between the two stations the frictional stress needed to balance the divergence of momentum may be obtained. This stress exports westerly momentum from the earth to the atmosphere if the surface wind is easterly and imports momentum from the earth to the atmosphere if the surface wind is westerly.

Table 1 gives the values of $\int_{1010}^{60} \overline{u'v'}dp$ and $\int_{1010}^{60} \bar{u}\bar{v}dp$ for Bahrein and Aden for each month of the year. The units are dyn $cm^{-1} \times 10^8$. On the average, frictional dissipation of excess momentum by surface westerly winds tended to balance the import of momentum from the earth by the deceleration of easterly winds.

9. Comparison with the Ahmadabad-Madras sector

Advective and eddy fluxes of momentum were also computed for a sector within the Indian subcontinent. The two stations used were Ahmadabad (23°04′N, 72°38′E) and Madras (13°00′N, 80°11′E). It was desired, in particular, to compare the divergence of the vertical integrals of momentum between the latter two stations with the divergence between Bahrein and Aden and to evaluate the momentum balance in terms of frictional stress of the surface winds.

The data used for Ahmadabad and Madras were collected during the period of the International Indian Ocean Expedition and were equivalent in quality and

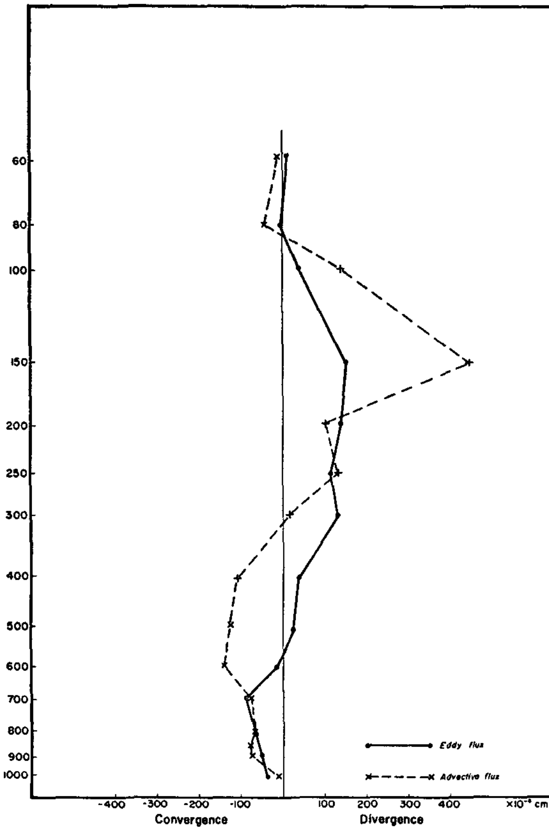

FIG. 10. Mean annual profile of the divergence of the eddy and advective fluxes of momentum within the Bahrein-Aden sector in 1962 (10^{-5} cm sec^{-2}).

TABLE 1. Vertical integral of the eddy and advective momentum fluxes for Bahrein and Aden, 1962. Units are dyn $cm^{-1} \times 10^8$.

	Bahrein		Aden	
	$\int_{1010}^{60} \overline{u'v'}\,dp$	$\int_{1010}^{60} \bar{u}\bar{v}\,dp$	$\int_{1010}^{60} \overline{u'v'}\,dp$	$\int_{1010}^{60} \bar{u}\bar{v}\,dp$
January	0.0	10.2	0.3	1.1
February	2.3	−3.3	0.3	−0.1
March	2.6	−9.4	0.7	−1.3
April	−1.5	2.1	−0.2	−0.1
May	−0.8	1.4	−0.2	0.6
June	0.2	−0.8	0.1	−1.2
July	−0.6	−0.1	0.1	0.1
August	−0.4	−0.1	0.5	0.4
September	0.1	−0.3	0.3	−0.4
October	−0.3	2.2	−0.1	0.5
November	−0.6	0.1	−0.2	0.5
December	2.1	−7.1	−0.1	−0.8
Mean	0.3	−0.4	0.1	−0.1
Export		0.2×10^8 dyn cm^{-1} eddy momentum		
Import		0.3×10^8 dyn cm^{-1} advective momentum		

TABLE 2. Vertical integral of eddy and advective fluxes of momentum at Ahmadabad and Madras in 1963. Units are dyn $cm^{-1} \times 10^8$. Values in parentheses refer to the station with approximate corresponding latitude in the Arabian sector.

	Ahmadabad		Madras	
	$\int_{1000}^{100} \overline{u'v'}\,dp$	$\int_{1000}^{100} \bar{u}\bar{v}\,dp$	$\int_{1000}^{100} \overline{u'v'}\,dp$	$\int_{1000}^{100} \bar{u}\bar{v}\,dp$
January	2.1 (0.0)	9.0 (10.2)	0.1 (0.3)	1.5 (0.1)
April	1.9 (−1.5)	−1.5 (2.1)	0.6 (−0.2)	0.1 (−0.1)
July	0.1 (−0.6)	−0.2 (−0.1)	−0.1 (0.1)	0.5 (0.1)
October	0.1 (−0.3)	−0.2 (2.2)	−0.1 (−0.1)	0.5 (0.5)
Mean	1.1 (−0.6)	1.8 (3.6)	0.1 (0.0)	0.7 (0.2)

detail to the observations used for Bahrein and Aden, but the periods used were different (January, April, July, October, 1963).

Table 2 shows the values of $\int_{1000}^{100} \overline{u'v'}dp$ and $\int_{1000}^{100} \bar{u}\bar{v}dp$ for the latter four months at Ahmadabad and Madras, where the values in parentheses refer to the stations with corresponding latitudes in the Arabian sector (Bahrein corresponding with Ahmadabad and Aden with Madras, respectively), for 1962. Table 3 compares the total (frictional) stress for both sectors in each of the four months.

The greatest frictional stress occurs in January for both sectors. The mean stress for the year, probably fortuitously, is the same for both sectors when computed for the four months concerned. However, the close agreement suggests that the frictional stress computed for this region is of the right sign when averaged over several comparable months. The maximum net divergence of momentum occurs in winter while in summer there is slight net convergence. This agrees with the synoptic climatology of the region. The northeast winter monsoon gains momentum from the earth while the summer southwest monsoon loses momentum to the earth. The results indicate that there is a net annual gain of earth momentum to the sector and that much of this import is transferred upward to the upper troposphere and lower stratosphere where it is exported.

10. Conclusion

The upper wind structure within the Bahrein-Aden sector in 1962 shows evidence of meridional circulations during much of the year at Bahrein and at Aden. The eddy flux at Bahrein shows a belt of equatorward flux in the lower troposphere for all months in 1962. Strong cores of poleward flux occur at 150–200 mb in the winter while equatorward flux occurs in the high troposphere and low stratosphere in summer. The eddy flux of momentum is much weaker at Aden than at Bahrein. The divergence of the eddy momentum flux suggests upward vertical flux predominating within the sector, particularly in winter.

The advective term is larger and more variable than the eddy term but the mean annual divergence profile of advective momentum also indicates upward vertical transfer. The total momentum balance indicates that momentum is gained from the earth in winter due to the frictional stress of the surface westerlies. These conclusions agree with the synoptic climatology of the region which suggests a mean surface easterly wind in winter and a mean surface westerly wind in summer. The magnitude of the frictional stress may serve, therefore, as a measure of the zonal wind strength at the surface.

The flux of momentum by synoptic scale eddies of the subtropical jet stream appears to be the more systematic and regular process for transporting momentum poleward at Bahrein. Transport in both directions by the meridional wind is irregular and tends to cancel out. At Aden the transport of momentum by eddies is less important. This result agrees with the conclusions of Tucker (1964) and others that the transport of momentum by eddies becomes greater with increasing latitude in the tropics.

The conclusions drawn for the Bahrein-Aden sector are supported by the results of the Ahmadabad-Madras sector which exhibit the same broad features for the four months analyzed.

TABLE 3. Total stress (dyn cm^2) in the Arabian and Indian sectors.

	Arabian sector	Indian sector
January	5.9	8.5
April	0.2	−0.4
July	−0.3	−0.3
October	1.5	−0.8
Mean	1.8	1.8

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