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Local influence on the SE trades of the west Indian Ocean

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ABSTRACT. Attempt has been made to explain the local variations of the SE trades in the lower levels during the northern summer at Diego-Suarez in Malagasy, Garissa in Kenya and Socotra in the west Arabian Sea. At Diego-Suarez the trades experience local acceleration which is ascribed to the increased pressure gradient caused by the Malagasy barrier. Kenya is situated east of the African barrier where, to the north of the equator, a pressure trough and to the south a pressure ridge are produced by the barrier. From the ridge to the trough an organised flow of air takes place up to north Somalia. This flow, across the equator over Kenya, can accelerate when the trough-ridge system intensifies. In the area of Socotra the thermally controlled pressure gradient is considered mainly responsible for the increased wind speed. Importance of the African barrier on the Indian monsoon is also discussed.

1. Introduction

During the northern summer the SE trades of the south Indian Ocean cross the equator west of about 70°E and reach the Arabian Sea where they are called the southwest monsoon current. In southern Asia the general pressure distribution in this season (Fig. 1) is such that as soon as the trades cross the equator as a weak current to the northern hemisphere, they become mainly westerly and gain speed. An exception to this is observed over a narrow belt between about 45°E and the African barrier. Here the trades reach beyond 10°N as an organised strong southerly current parallel to the African barrier (Figs. 2 and 3). Curiously, north of Somalia where the barrier ends, the southerly component of the trades becomes comparatively weak and they eventually merge with the seasonal westerlies north of 10°N in the Arabian Sea. Apparently the barrier produces certain pressure distribution which is favourable for the trades to get organised as a southerly current over eastern Africa and the adjoining seas.

Recently Findlater (1971) made a commendable compilation of the low-level wind data for the region comprising the west Indian Ocean, eastern Africa and the Arabian Sea. His analysis reveals that during the northern summer the trades from Malagasy (Madagascar) to the Arabian Sea undergo appreciable local variations in speed in the lower levels below about 3000 m.

There are three distinct areas where the mean winds in the lower levels are relatively strong throughout the season. They are (*i*) Diego-Suarez (12°21′S, 49°18′E) in Malagasy, (*ii*) Garissa (00°29′S, 39°38′E) in Kenya and (*iii*) Socotra (12°38′N, 53° 53′E) in the west Arabian Sea (Fig. 4). From the data compiled by Findlater (1971) it appears that the average level of maximum wind at Diego-Suarez and Socotra is about 900 m while it is around 1500 m at Garissa. The mean direction and speed of winds for the representative month of July given in Figs. 2 and 3 reveal that upstream from Diego-Suarez, Garissa and Socotra the wind speeds are appreciably small. This seems to suggest that in the vicinity of these stations there are factors that are favourable for the trade winds to get locally accelerated during the season.

Socotra was an upper wind station for a couple of years during the World War II. It recorded winds over 40 kt on 20 occasions at about 1000 m during the period June to August 1943 (Meteorological Office, London 1944). During August-September 1964 Bunker (1965) observed a wind speed of about 50 kt at 1000 m near Socotra. For Garissa in Kenya information on extreme winds for the period 1962-64 has been compiled by Findlater (1966). This being a pilot balloon station the wind data are missing on many days in a month mostly due to strong winds. July 1973 was an exceptional month when both the forenoon (04 GMT) and afternoon (10 GMT) ascents reached a height of 1500 m on 17 days. These are given in Table 1 to show that extreme winds are mainly a forenoon phenomenon which seldom lasts more than 6 hours.

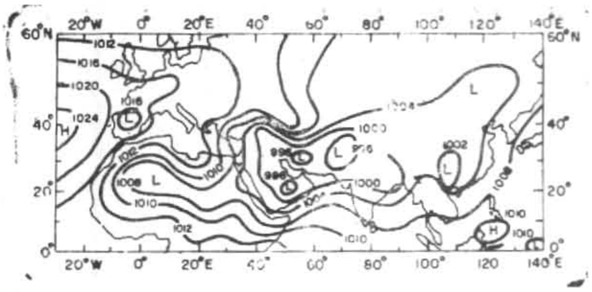

Fig. 1. Normal sea level pressure (mb) in July over India and neighbourhood. 1002 and 1010 mb isobars are odd isobars

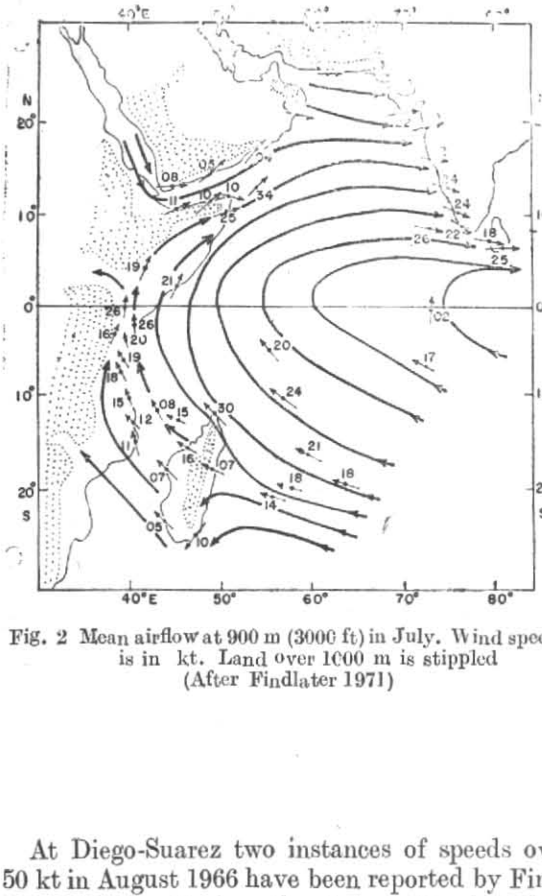

Fig. 2 Mean airflow at 900 m (3000 ft) in July. Wind speed is in kt. Land over 1000 m is stippled (After Findlater 1971)

At Diego-Suarez two instances of speeds over 50 kt in August 1966 have been reported by Findlater (1969). During the International Indian Ocean Expedition (1963-64) upper wind observations for standard levels 900 mb (1000 m) and 850 mb (1500 m) were received routinely for Diego-Suarez. During August 1964 there were 74 observations for 1000 m of which 18 reported winds 40-50 kt, one 52 kt and the rest (55 observations) recorded winds below 40 kt. Out of a total of 53 observations at 1500 m six recorded 40-50 kt, one 66 kt and the rest (44 observations) recorded winds below 40 kt.

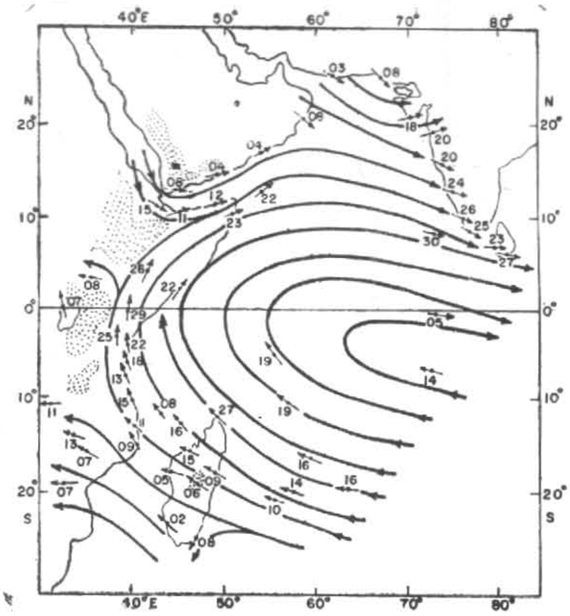

Fig. 3 Mean airflow at 1500 m (5000 ft) in July. Wind speed is in kt. Land over 1500 m is stippled (After Findlater 1971)

We propose to make here an attempt to understand the probable factors that influence the local variations of the speed and direction of the trades. Considering the severe restrictions imposed by the lack of data over mountains, deserts and seas which are the areas of primary interest to us, our findings are not expected to be conclusive but only suggestive. They may be useful, however, for a planned study of the phenomenon in future.

2. Local peculiarities

Since the acceleration of wind is apparently caused locally over a limited area around Diego Suarez, Garissa and Socotra it is necessary in the first instance to look for local peculiarities in the low-level circulation particularly in the light of orographic features. These peculiarities need not be identical at the three areas and therefore each area is considered separately.

3. Orographic winds over Malagasy

Almost in the centre of Malagasy runs a north-south barrier with an average height of about 1000 m. Diego-Suarez (altitude 8 m) is situated in the coastal plains nearly 20 km north of this barrier. Farther north is the Cap d' Ambre which is the northernmost point of Malagasy.

In the latitudes of Malagasy in the Indian Ocean the general direction of the SE trades in the lower level is 110°-115°. As they reach Malagasy they

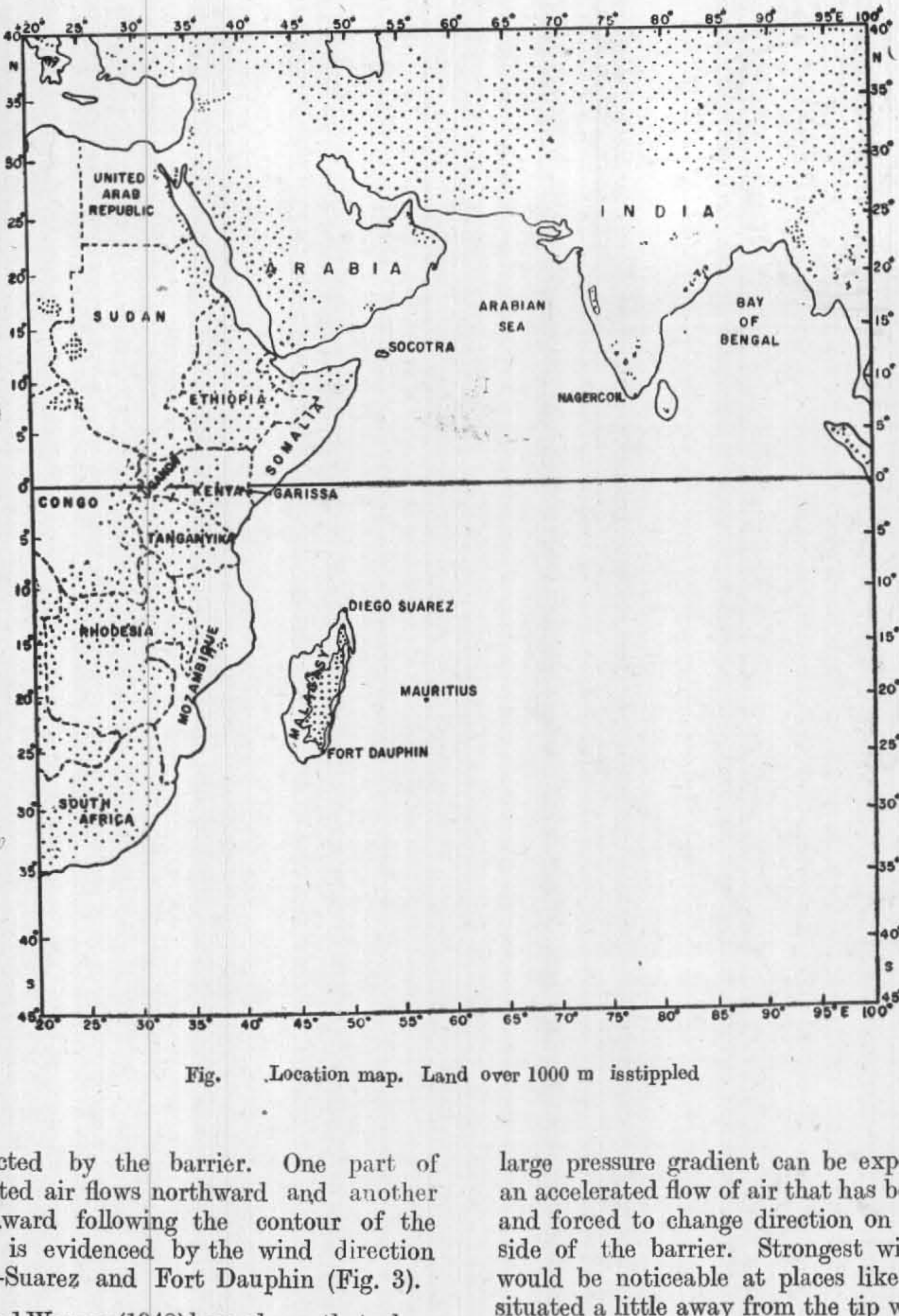

Fig. .Location map. Land over 1000 m isstippled

are obstructed by the barrier. One part of the obstructed air flows northward and another part southward following the contour of the barrier, as is evidenced by the wind direction over Diego-Suarez and Fort Dauphin (Fig. 3).

Hess and Wagner (1948) have shown that when winds blow across a barrier a ridge of high pressure normally develops on the windward side and a trough of low pressure on the lee side. On the windward side of the Malagasy barrier we therefore notice normally a sharp displacement of sea level isobars from the region of higher pressure in the south toward the region of lower pressure in the north (Thompson 1965). This would lead to an increase of pressure gradient near the northern tip of the barrier as can be readily seen from Fig. 5. Over this area the large pressure gradient can be expected to cause an accelerated flow of air that has been obstructed and forced to change direction on the windward side of the barrier. Strongest winds, however, would be noticeable at places like Diego-Suarez situated a little away from the tip where the frictional effects of the barrier are less.

4. Equatorial drift in Kenya

During northern summer the circulation over southern Africa up to about 2000 m is controlled by a pressure trough with its axis running north-south over the central parts and a pressure ridge extending south to north along the east coast (Tajaard *et al.* 1969). Though the basic flow is easterly the trough-ridge system introduces a meridional component to the basic flow.

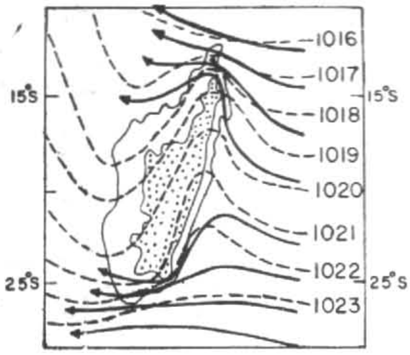

Fig. 5. Normal low-level stream flow of air and sea level pressure (mb) over Malagasy during northern summer. Land over 1000 m is stippled. A big dot in the north is Diego-Suarez

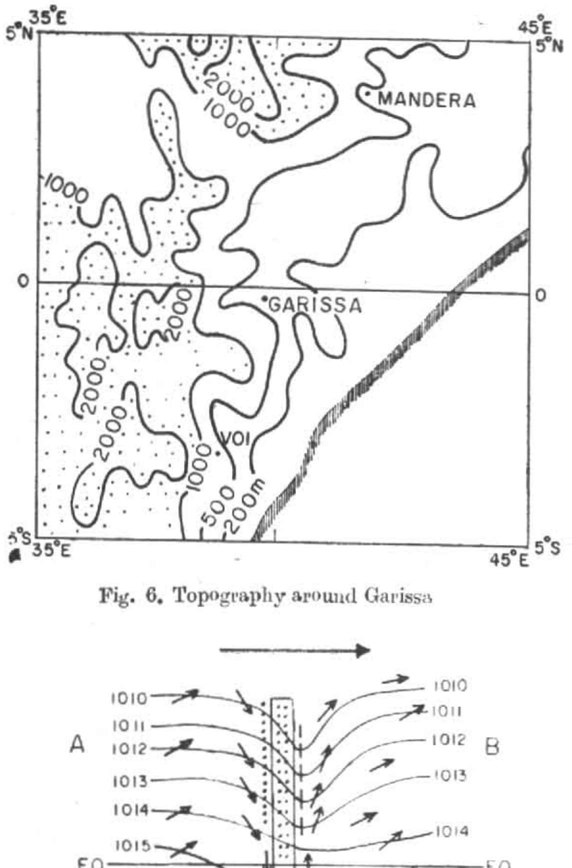

Fig. 6. Topography around Garissa

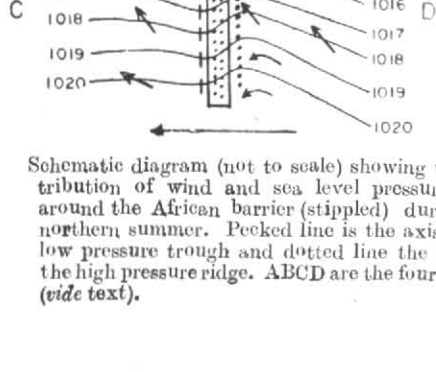

Fig. 7. Schematic diagram (not to scale) showing the distribution of wind and sea level pressure (mb) around the African barrier (stippled) during the northern summer. Pecked line is the axis of the low pressure trough and dotted line the axis of the high pressure ridge. ABCD are the four sectors (*vide* text).

The trough-ridge system of southern Africa practically vanishes north of the equator where the basic flow in the lower levels is mainly controlled by the seasonal trough of low pressure extending from Arabia to West Africa roughly along 15°N (Fig. 1). South of about 15°N up to the equator, therefore, the prevailing winds are mainly from the west. The vertical extension of these westerlies increases from 600-1200 m at the coast of West Africa to 2600-3000 m along the river *Nile* and 5000-5500 m over India (Flohn 1962).

Garissa (height 128 m) is situated about 50 km south of the equator at the foot of a range of hills of average elevation of about 1500 m (Fig. 6). As an unbroken barrier the hill-range runs almost meridionally from about 15°S to 5°N as part of the African mountain complex (average elevation 1000 m). Northward beyond 5° N, it extends, after a small gap, as far as north Ethiopia and Somalia where its average height is nearly 2000 m.

North of the equator the barrier is embedded in the westerlies and south of the equator in the easterlies. In the north over Kenya and Somalia situated in the lee of the barrier we should normally expect a trough of low pressure close to the barrier. Similarly in the south the easterlies would cause a ridge of high pressure over the coastal region which is situated close to the barrier on its windward side.

Over Kenya where the equator marks the normal boundary between the orographic ridge and trough, an interesting phenomenon can develop under favourable conditions. This may be easily appreciated by referring to Fig. 7 where the pressure distribution is schematically depicted for the four sectors, *viz.*, the windward sector (A) and leeward sector (B) of the barrier north of the equator where the basic flow is westerly, and similarly the leeward sector (C) and windward sector (D) of the barrier south of the equator where the basic flow is easterly. Close to the equator where the coriolis force is negligible the orographic ridge and trough would be insignificant, but away from the equator, with the increase of coriolis force, they would become distinct pressure systems. Note that the orographically induced pressure and wind are superposed on the basic flow so that the trough in sector (B) will be reinforced while that in sector (C) will be weakened by the basic flow. Similarly, the ridge in sector (A) will be weakened while that in sector (D) will be reinforced by the basic flow.

This type of pressure distribution on either side of the equator is favourable for causing

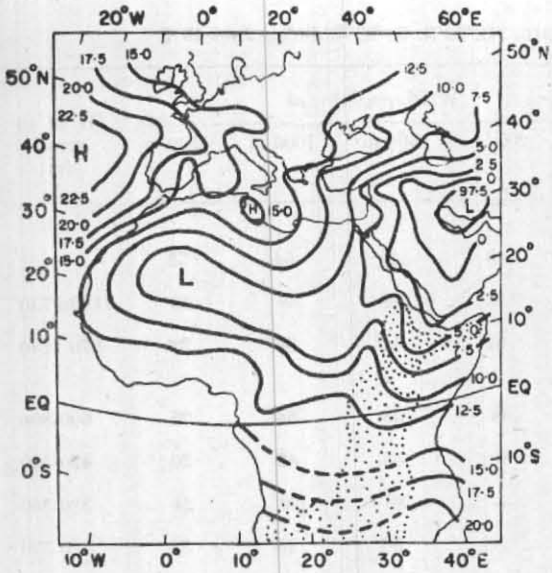

Fig. 8. Normal sea level pressure (mb) in July over Africa (After Amer *et al.* 1969). The values are 997·5, 1000·0, 1002·5 mb etc. The land over 1000 m is stippled

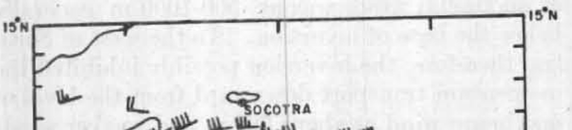

Fig. 9. Winds at 900 mb (1000 m) observed by the Russian research vessel *Shokolaisky* during her cruise west to east from 18 to 22 June 1973

for a while large pressure gradient across the equator leading to cross-isobaric explosive drift of air from the south to north across the equator. Johnson and Morth (1960) have termed this type of drift as 'equatorial drift'.

Recently Amer *et al.* (1969) prepared for northern Africa the mean sea level pressure chart for the representative month of July. Extending this to southern Africa in the light of the charts by Thompson (1965), a complete pressure chart for the African continent is given in Fig. 8.

As pointed out earlier Fig. 8 depicts the orographic pressure ridge in southern Africa on the windward side of the barrier. In northern Africa to the west of the barrier on the windward side also we notice a similar ridge. Corresponding to this ridge we should expect to the east of the barrier a lee-trough. In Fig. 8 the lee-trough, however, is displaced a little to the west over the crest of the barrier. This is because there is not a single observatory at the foot of the barrier on the lee-side. This is a serious handicap to make a conclusive study of the characteristic features of the low level winds in relation to the lee-trough.

TABLE 1

Wind speed (kt) over Garissa during July 1973

Date Jul. 1973	Height (feet)					
	3000		4000		5000	
	04 (GMT)	10	04 (GMT)	10	04 (GMT)	10
2	23	9	33	12	28	9
3	44	37	55	47	57	32
4	37	15	47	22	49	22
6	44	62	36	20	30	18
10	50	24	69	32	63	28
11	41	17	55	19	53	20
12	41	30	43	32	39	48
13	44	33	45	33	37	51
14	54	15	38	19	31	125
16	27	14	29	22	25	19
17	38	30	37	35	60	31
18	32	41	33	18	33	20
19	39	36	45	19	39	30
23	14	41	49	38	41	9
27	30	34	32	39	36	48
28	21	12	42	20	42	20
30	37	22	55	34	53	28
Mean	36	28	44	27	42	27

Orographic ridge and trough may extend almost up to the height of a barrier. In our case the height of the barrier is 1500-2000 m below which is the usual regime of the strong winds of jet speed over Kenya. In the afternoons when the eastern slope of the barrier gets warmed up, the resulting low pressure all along the slope may weaken the pressure gradient in the lee-trough. This may contribute to a significant weakening of the low level winds in the afternoons as can be seen from Table 1.

5. Seasonal pressure and winds around Socotra

Socotra (ht. 44 m) is an island station situated in the west Arabian Sea. To the north is Arabia where the seasonal trough of low pressure is intense (Fig. 1). To the southwest lies Somalia which is mostly dominated by a well marked ridge of high pressure.

Between this ridge and the trough there is a large pressure gradient over north Somalia, south Arabia and the adjoining seas including the west Arabian Sea around Socotra. Associated with the large pressure gradient one would normally expect strong winds in the lower levels of the region but the winds in general are weak except around Socotra (Fig. 2). Analysis of mariners' reports within the latitudinal belt 12°-15°N shows that during July and August the surface winds of speeds 44 kt or more occur once in a month in the area to the west

TABLE 2

Observations taken by S. V. *Shokolaisky* **near Socotra (12°38′N, 53°53′E) during June 1973**

Time (GMT)	Location		Sea temp. (°C)	Sea *minus* air temp. (°C)	Wind speed (kt) at					Ht. of inversion (m)
	Lat. (N)	Long. (E)			Surface	200 m	500 m	1000 m	1500 m	
					June 8					
00	10°30′	58°06′	27·4	−0·2	36	48	40	54	52	
12	10°18′	57°12′	27·4	−1·0	38	44	44	56	40	1190-1730
18	11°00′	56°30′	27·5	−0·8	38	44	42	50	32	970-1280
					June 10					
00	11°36′	54°42′	25·9	−1·9	32	44	58	54	28	600-800
06	12°00′	53°42′	26·4	−0·7	34	40	58	42	20	420-550
12	12°12′	52°48′	25·6	−0·7	36	—	38	20	24	320-550
18	12°24′	51°54′	26·0	−1·8	20	24	06	18	34	120-370
					June 11					
00	12°30′	50°42′	30·3	−0·5	10	10	20	22	22	0-100
06	12°30′	49°42′	29·9	−1·5	10	08	26	22	30	250-730

of Socotra (51°-54°E) whereas to the east of Socotra (55°-57°E) they occur on about 6 days in a month (Meteorological Office, London 1944). The low-level wind observations taken by the Russian research ships during the Indo-Soviet Monsoon Experiment (ISMEX) 1973 also have revealed more or less the same features (Fig. 9).

In the west Arabian Sea near the Somalia coast the seas are cold and low-level inversions are common. These inversions can influence wind speed. In the normal atmosphere with no inversion one can expect turbulent transfer of momentum from the level of stronger winds at the top of the planetary boundary layer to the levels below this level so that the frictional dissipation of wind speed in the lower levels is partly compensated for. When there is inversion within the boundary layer the downward transfer of momentum is restricted since the inversion layer acts like a lid and the frictional dissipation of wind speed becomes more marked.

In order to understand the influence of inversion on the wind speed in the area west of Socotra we have examined the observations recently taken by the Russian research vessel *Shokolaisky*. In Table 2 are given the relevant data compiled aboard *Shokolaisky* during one of her cruises across the Arabian Sea to the Gulf of Aden when there was no major change in the seasonal circulation pattern. They show that west of Socotra the base of the inversion generally decreased in height and the level of maximum wind was above the base of the inversion around 500 m. East of Socotra the level of maximum wind was at 500-1000 m generally below the base of inversion. To the west of Socotra, therefore, the inversion possibly inhibited the momentum transport downward from the level of maximum wind at about 500 m and weaker winds prevailed below 500 m compared to the winds east of Socotra. Another important fact seen from Table 2 is that near the top of the boundary layer around 1000 m also the magnitude of the maximum wind is remarkably small west of Socotra compared to the east. This prompts us to look for other factors that seem to influence the winds beyond the boundary layer also in the area to the west of Socotra.

Northwest of Socotra over Arabia lies a thermal low (Fig. 1) extending up to about 1000 m. It rapidly changes aloft into an anticyclonic circulation. The thermal wind west of Socotra would be from a northeasterly direction which can lead to a weakening of the lower level westerlies.

Moreover, Socotra is situated almost at the mouth of the Gulf of Aden (Fig. 4). To the north, west and south of the Gulf lie mountain ranges over 1 km in elevation. The seasonal westerlies in the lower levels strike these ranges and experience frictional convergence before reaching the Gulf of Aden and beyond. In this process the winds at least upto the height of the mountain ranges would suffer a reduction in speed.

Away from the orography at about Socotra and further east where the base of inversion is generally above the level of maximum wind we notice stronger winds which we expect from the prevailing pressure gradient. Recently Saha (1974) made a comparison of the geostrophic wind with the actual wind near Socotra. He obtained a geostrophic wind of 66 kt against the observed wind of about 40 kt at surface level. His computation was however based on a composite chart of 17 surface observations spread over a period of one month (August 1963). Since the daily variations of pressure and wind speed in the west Arabian Sea are remarkably large, it was thought desirable to examine the simultaneously observed pressure and wind distribution in order to understand the geostrophic control on the strong winds in the vicinity of Socotra. For this the observations obtained during the ISMEX 1973 have been utilized.

6. Wind-pressure relationship near Socotra

To examine this aspect occasions were chosen when a ship, particularly a research vessel recorded surface wind of 30 kt or more in the vicinity of Socotra. To enable a reasonable analysis of the sea level isobaric field, atleast four additional ships within about 300 km to represent each quadrant were also found necessary. Occasions satisfying these conditions were only 11 during June-July 1973 and the analysis of the sea level isobaric field conducted on the basis of the observations from all the ships and land stations appeared to be fairly satisfactory to examine the general relationship.

From the analysed pressure field horizontal pressure gradients were picked out at 2-degree latitude/longitude grid-box centred on the central ship of wind speed 30 kt or more. It has been found that in the region of Socotra the average geostrophic wind speed (based on the eleven sets of data) is 54 kt and the observed speed 32 kt, the average angular difference between the streamlines and isobars being 34° pointing towards the area of lower pressure. It may be pointed out that the observed wind speed $/V/$ is a local average while the geostrophic speed $/V_g/$ refers to synoptic scale since it is computed on the basis of smoothed pressure gradient over a distance of about 400 km.

The ratio between $/V/$and V_g in our case works out to 0.60 which is comparable with the values observed elsewhere in the tropical region (Brumer *et al*. 1974). Since we have taken into account neither the friction nor the wind structure throughout the boundary layer, it is natural that the observed wind is sub-geostrophic. According to Bunker (1965) there is a sharp increase in the winds aloft, and at about 1000 m, which is perhaps the top of the planetary boundary layer, the maximum winds are recorded in the area of Socotra. ISMEX 1973 data also support this as the ships have reported winds of 50-60 kt around 1000 m.

7. Summary and remarks

During the northern summer when the SE trades reach Malagasy, a large pressure gradient is caused by the Malagasy barrier near its northern end. This orographically induced pressure gradient seems so be mainly responsible for the strong winds in the lower levels over Diego-Suarez which is situated about 20 km equatorward of the northern end of the barrier. After experiencing the local acceleration over Diego-Suarez, the trades gradually weaken downstream in the region of Mozambique channel. As they advance west of the channel over eastern Africa they are obstructed by the African barrier. The obstructed stream develops a pronounced ridge of high pressure on the windward side of the barrier. Part of the air from the high pressure ridge would flow north. After crossing the equator over Kenya it comes under the influence of the pressure gradient that prevails in the orographic trough of low pressure which the seasonal westerlies of northern Africa generate all along the lee side of the African barrier from Kenya to Somalia. As the pressure ridge south of the equator and the trough north of the equator become significant, the pressure gradient near the equator over Kenya may increase leading to an explosive drift of air (jet) south to north across the equator where the coriolis force is negligible. Normally the ridge of high pressure may serve to continuously pump out air across the equator into the lee-trough over Kenya and Somalia.

The trough of low pressure in the lee of the barrier over Kenya and Somalia could not so far be located satisfactorily due to lack of observations close to the barrier and, therefore, we have inferred its presence from dynamical considerations. This trough deserves to be observationally explored particulaly because of its possible role in maintaining the pressure gradient that is necessary to cause an organised flow of the trades as far as the northern end of the barrier in Somalia. We are tempted to believe that but for the barrier and its associated lee-trough in northern Africa, the SE trades might have crossed the equator as a weak current restricted to south of about 5°N as we notice in the east Arabian Sea. In that case, north of about 5°N the dry continental westerlies of northern Africa, which are several degrees warmer than the Arabian Sea surface, might possibly bring about a substantial change in the nature, distribution and amount of monsoon precipitation in the Arabian Sea and the adjoining regions.

After the main core of the trades reaches the northern end of the axis of the lee-trough over Somalia it emerges into the west Arabian Sea north of about 10°N where there is a steep pressure gradient. Near Socotra the conditions are favourable for the winds to accelerate under the influence of this pressure gradient.

It is unfortunate that the local acceleration of winds occurs in the data-sparse regions of mountains or seas. The explanations offered here are tentative and they undoubtedly need more observational support particularly in regard to the development of lee-trough over Kenya and Somalia. We suggest that atleast one surface observatory may be established in south Somalia close to the mountain barrier and another to its east at the coast during the MONEX 1978-79.

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