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Variations in Upper Tropospheric Flow associated with the onset of the Australian Summer Monsoon

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ABSTRACT. Characteristics of the onset of the summer (northwest) monsoon in North Australia, and of the mean upper tropospheric flow in the east Indian Ocean—Australian region are discussed. The strength and steadiness of the upper flow are much less than that over Asia in the corresponding season. Nevertheless, the monsoon onset is shown to be associated with marked changes in the upper flow; in the tropics the easterlies increase, and the subtropical jetstream shifts southward abruptly. The changes also extend to low latitudes of the Northern Hemisphere. They appear to be the result of large-scale development rather than the movement of individual disturbances.

1 Introduction

Over the past decade, considerable knowledge has been gained of the marked and abrupt changes in the high troposphere over Asia, which are linked with the inception of the summer monsoon. Several workers have pointed out such major features of the transition from winter to summer as the disappearance of the polar tropopause in subtropical latitudes, the dissolution of the very strong and persistent westerly jetstream south of the Himalayas, and the establishment of an easterly jet centred just below the tropopause at about fifteen degrees north latitude (see for example Yin 1949, Frost 1953, Staff Members Academia Sinica 1957, Koteswaram 1958). A recent work on momentum balance considerations in a monsoonal region (Berson and Troup 1960) has pointed out the intimate connection between monsoonal low-level westerlies and the strength and position of the upper easterly current, at least on a seasonal basis. It would, therefore, be expected that similar changes to those occurring over Asia would be found in other monsoonal regions, though perhaps not to such a marked extent.

The present study investigates such changes in connection with the onset of the Australian summer monsoon for four individual seasons. After establishing dates of onset, a brief examination of the mean flow and a comparison with the Asian region is made. Upper wind data are then studied in some detail for four low-latitude stations (Darwin, Cocos Island, Singapore and Port Hedland), and other observations are also considered more briefly. The behaviour of the subtropical jetstream at 135°E is also related to the onset of the monsoon.

2. The Australian Summer Monsoon

The region considered for specification of monsoon onset is that of Darwin and its neighbourhood. The monsoonal bursts are regarded, following Palmer (1952), as due to the movement of cyclonic vortices, often small in horizontal extent and weak in pressure gradients, along preferred tracks which tend to be displaced further poleward as summer progresses. Evidence for the importance of such disturbances is given by Hannay (1945) who considers that deep monsoonal westerlies are nearly always associated with the development of tropical cyclones. The onset, which is the first of these "bursts", can then be somewhat arbitrarily determined either by the change in wind regime or by the changes of precipitation recorded.

An examination of both criteria has been made for the Darwin region for four "wet" seasons, *viz.*, the months November to March 1955/6 to 1958/9, to connect these with changes in the upper wind regime over a

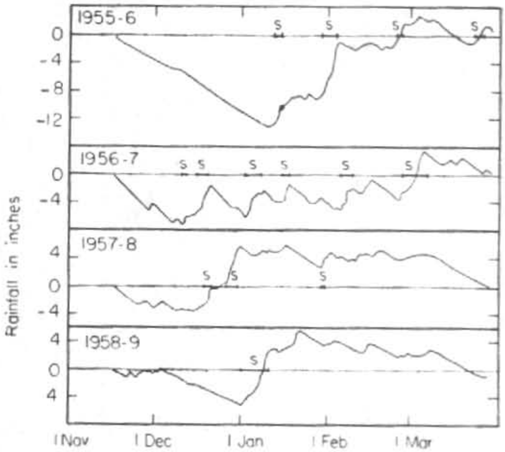

Fig. 1. Cumulative residuals of Darwin area rainfall (inches)

Spells of heavy rain indicated by S

wide area; prior to the first of these seasons there are insufficient regular high-level wind observations.

The rainfall has been considered in terms of spells of heavy rain, by a method similar to that used by Ramakrishnan and Narayanan (1955) in a study of rainfall at Mangalore. In the Darwin region conditions are similar to those in low latitudes in India, and the monsoon onset occurs as the culmination of a period of disturbed weather, in which thunderstorms and line-squalls become more frequent (R.A.A.F. Meteorological Services, 1942). It is, therefore, preferable to consider area rather than single-station rainfall, to reduce the importance of isolated heavy thunderstorm falls. Daily rainfalls for six stations, available in the *Australian Daily Weather Report*, in the Darwin region have been used. These are: Darwin, Pine Creek, Oenpilli, Cape Don, Croker Island and Goulburn Island; their location is shown in the inset to Fig. 2. It would be expected from effects of coastal convergence, and from the orientation of the mean intertropical convergence zone in the region, that the correlation between rainfall at individual stations would decrease much more rapidly in a direction normal to the coastline, than in one parallel to it, as has been shown for seasonal falls by Treloar (1934); so that the stations have been chosen with a weighting towards coastal observations.

Days were only considered as raindays when four or more of the stations recorded rainfall. The average rainfall on each rainday was then obtained; this quantity will be referred to below as the "area rainfall". This selection excludes a considerable portion of the rainfall recorded early in the season; thus in these four seasons fiftysix per cent of the total rainfall was excluded in November, but only twelve per cent in January, indicating the quite different nature of rainfall distribution in these two months.

The definition of a spell of heavy rain is similar to that of Ramakrishnan and Narayanan (1955); a spell occurs and lasts for N days when the total rainfall for those days exceeds $0\cdot75$ $(N+1)$ inch. The factor $0\cdot75$ is used instead of the factor 2 used by these authors, because the rainfall in the region is half of that at Mangalore, and also because area rather than single-station rainfall is considered. Two further restrictions are made on spell length; first, a spell is concluded when the area rainfall on any day is zero, or when on two consecutive days the rainfall is less than $0\cdot75$ inch, and second, days with rainfall less than $0\cdot75$ inch at the beginning and end of a spell are excluded.

In these four seasons the number of spells is respectively four, six, three and one; these are comparable with the number of spells at Mangalore, and also with the number, *viz.*, 3 to 4 per year, given by Hannay (*loc. cit.*) of incursions of the ITC into the Darwin region.

Graphs of cumulative residuals of the area rainfall (accumulated departures from the average area rainfall for each individual season) are shown in Fig. 1, with the spells indicated. It can be seen that in three out of the four seasons there is an abrupt change from negative to positive slope, corresponding to the first heavy rain spell, which initiates a rainfall regime with short-period slope changes but with an average slope approximating zero. These graphs effectively demonstrate the intermittent nature of monsoon rainfall in the region.

Spells of moderate west wind at Darwin have also been noted, using the zonal component of the three thousand foot wind at 04 GMT (first 2 seasons) or 23 GMT (second two seasons), the time of the rawin sounding. A spell of moderate west wind occurs and lasts for N days when the cumulative zonal component (eastward positive) exceeds $10(N+1)$ knot; it is concluded when this component is less than five knot on two consecutive days.

The spells of heavy rain and the west wind spells are listed in Table 1. The mean vector winds during the rain spells are also included. It will be seen that heavy rain is associated with moderate west winds, except for some occasions at the beginning and end of the season. A clear-cut monsoon onset occurs in two cases, *viz.*, on 13 January 1956 and 1—3 January 1959; in the other two the rain onset differs from the wind onset, and it appears preferable to state that the monsoon commenced over the periods 8—15 December 1956 and 19—28 December 1959.

An examination of westerly wind spells from 1951/2 to 1959/60 shows that in seven of these nine seasons the first spell began between 25 December and 20 January, dates agreeing broadly with the normal time of the first two weeks of January (R.A.A.F. Met. Services, *loc. cit.*). The 1956/7 season must therefore be anomalous, although a comparable date is given by Hannay for the 1944-5 season; this will be referred to in Section 4

TABLE 1

Spells of heavy rain and of westerly wind in the Darwin area

(All dates Greenwich dates)

Season	Rain spells	Mean 3000 ft vector wind during rain spell		West wind spell
1955/6	12—14 Jan	250°	12 kt	12—20 Jan
	29 Jan-4 Feb	No data		[2]—14 Feb
	25—27 Feb	285	17	18 Feb—11 Mar
	24—27 Mar	170	14	
1956/7	11 Dec	290	12	8—27 Dec
	15—19 Dec	250	21	
	3—8 Jan	255	26	2—16 Jan
	16—17 Jan	335	16	
	5—9 Feb	225	18	1—5 Feb 8—20 Feb
	27 Feb—9 Mar	300	12	4—10 Mar
1957/8	19—20 Dec	030	12	
	27—30 Dec	250	24	28 Dec—7 Jan
	30 Jan	260	13	29—30 Jan
				11—16 Feb
				26—31 Mar
1958/9	1—10 Jan	305	20	3—30 Jan
				15—16 Feb

3. The Mean Flow in the Upper Troposphere

In considering the possibility and magnitude of abrupt transitions of wind regime, it is necessary to bear in mind the climatology of the upper flow in the region. Fig. 2 shows the streamlines and isotachs of the mean 200-mb (40,000 ft) February flow. The observations on which this chart is based are taken mainly from the published mean values (Ramage 1959, Lamond 1959, Clarkson 1958) and vector means are plotted for stations with at least three years of observations. Values for Cocos Island and Lae, and additional years for Darwin, have been computed from manuscript data kindly supplied by the Australian Bureau of Meteorology. In analysing the chart, account has been taken of

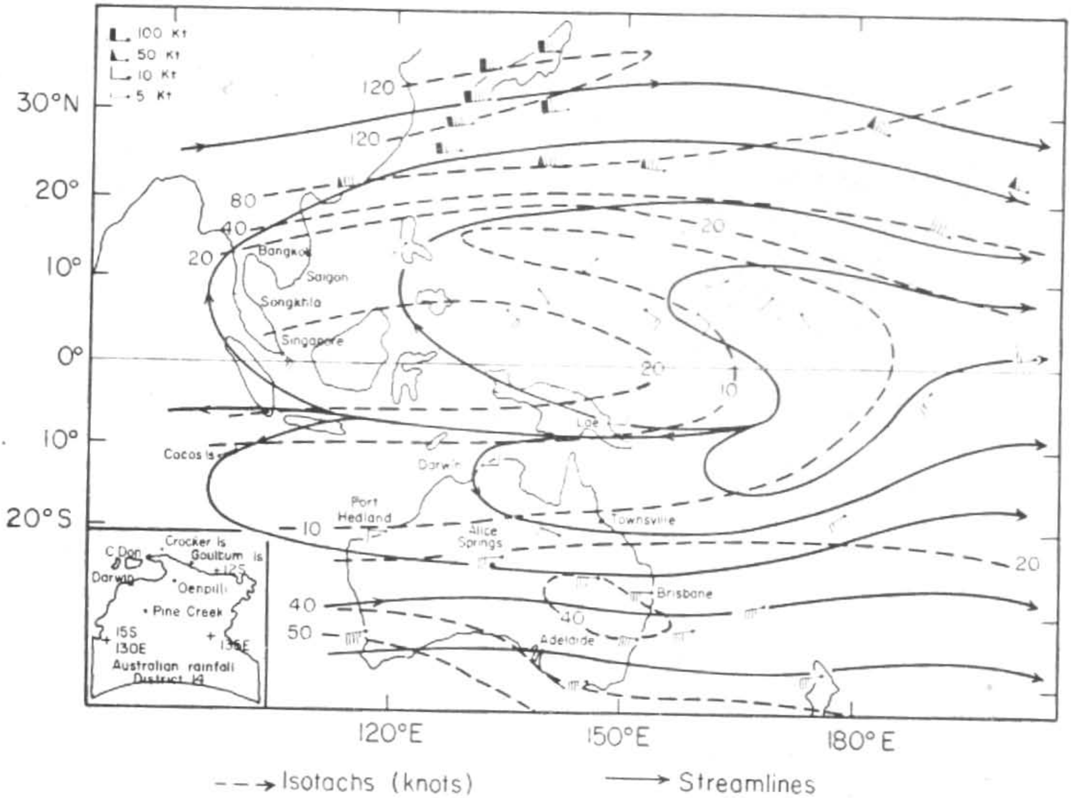

Fig. 2. Mean 200-mb (40,000 ft) flow, February

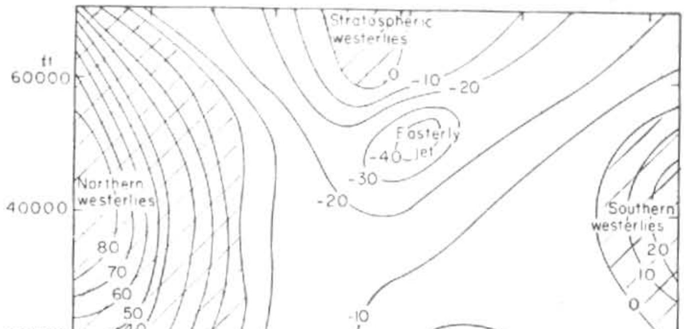

Fig. 3. Schematic cross-section of zonal wind (knots) at 110°E, January

shorter series of observations, pilot balloon data, and other charts of the region. Because of absence or inadequacy of data from large areas, and of differing lengths of record, in a season where the flow is very variable from year to year, the analysis can only broadly portray the features of the flow.

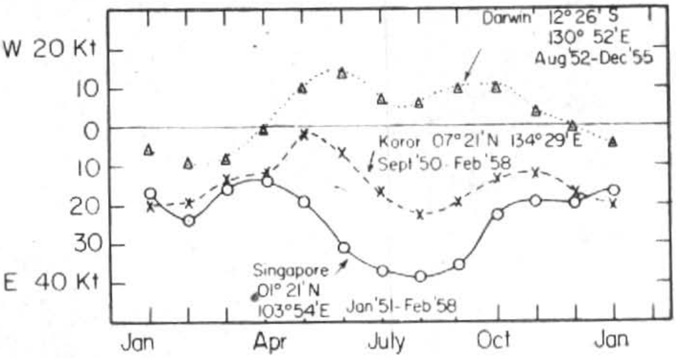

Fig. 4. Annual variation of zonal components at 200 mb

Noteworthy among these is the belt of comparatively strong easterlies extending from Malaya to New Guinea, and well into the Northern Hemisphere. This is associated with the monsoon flow and with the doldrum area south and southeast of the Phillipines. Upper easterlies appear to be absent further east in the west-central Pacific.

The vertical structure of the upper flow is indicated in the generalised cross-section of Fig. 3, which is based on one published by Ramsey (1955) for January 1954 at 110°E. It is modified and extended to higher levels by consideration of the published mean data. The easterly maximum is located at about 50 thousand feet near the equator; further south it slopes upwards to merge with the summer subtropical maximum above the tropopause. This easterly jet is not a feature of the West Pacific in Southern Hemisphere summer; the cross-section of Baliff *et al.* (1958) shows only the stratospheric maxima.

The seasonal variation of the flow is somewhat complicated in the low latitudes, several stations in both hemispheres showing evidence of a semi-annual oscillation of east component. The evidence available suggests that the strongest upper easterlies in the monsoon regions prevail in February and August. Variations for some stations in or adjacent to these areas are shown in Fig. 4.

It can be seen from such observations that the upper easterlies in southern summer are considerably weaker as well as less extensive in latitude than those which flow over the Asian summer monsoon. They are also less persistent, and the percentage variability from year to year is greater. Since the winter westerlies in corresponding latitudes are approximately the same in strength, one might expect that transitions between winter and summer flow patterns might be less marked in the Southern Hemisphere; in fact, however, the changes which occur can be both abrupt and of considerable magnitude.

There is considerable variation in the upper flow from year to year, in the region of strong easterlies as well as in latitudes further south, whether the season as a whole or individual months are considered. Radok and Grant (1957) point out that in some summers an anticyclone or ridge is established over the Australian continent, while in others this does not occur. At Singapore we find values of 50,000 ft vector mean wind ranging from 8 kt in February 1954 to 51 kt in February 1955 (Clarkson 1958). Such variations may be ascribed to relatively small displacements of the major wind systems in the vertical or horizontal particularly in regions of strong mean gradients; there is however, some evidence (Berson and Troup, *loc. cit.*) that they represent major changes in the

TABLE 2

Mean percentage departures of Northern Rivers monthly rainfall, related to monthly mean departures of Darwin-Alice Springs 200-mb height difference

Height difference grouping	<—50	—40 to —20	—10 to 10	20 to 40	>40
Mean height difference (metres)	—68	—28	—1	+28	+68
Rainfall departure (per cent)	+43	+12	—2	— 9	—38
No. of observations of					
Positive departures	4	9	8	3	1
Negative departures	1	4	12	14	4

TABLE 3

Marked changes of upper flow in East Indian Ocean Region

	Darwin 45,000 ft	Cocos I 40,000 ft	Singapore 40,000 ft	Port Hedland 40,000 ft	Shift of jet at 135°E 200 mb	Monsoon onset
			1955-56			
Transition dates	13—15 Jan	2—5 Jan	Not observed	8—9 Jan	10—11 Jan	12 Jan
Mean zonal comp.						
prior to change $\overline{U}_p$*	+ 0·4	— 5·1		+31·8		
Subsequent $\overline{U}_s$*	—14·0	—16·3		+ 3·3		
			1956-57			
Dates	14—18 Dec	4—6 Dec	27—29 Nov	19—21 Dec	15—20 Dec	8—15 Dec
$\overline{U}_p$	+ 9·6	+12·9	— 7·0	+41·0		
$\overline{U}_s$	—23·3	— 9·9	—25·9	+ 5·8		
			1957-58			
Dates	20—22 Dec	3—6 Dec	3—5 Dec	No transition	22—22 Dec	19—28 Dec
$\overline{U}_p$	+16·8	+19·6	+ 0·4	Temporary		
$\overline{U}_s$	—14·7	+ 6·3	—22·6	Change only		
			1958-59			
Dates	8—10 Jan	17—18 Dec	13—15 Dec	30—31 Dec	11—12 Jan	1—3 Jan
$\overline{U}_p$	+ 7·0	+13·9	—10·8	+59·4		
$\overline{U}_s$	—15·9	— 3·9	—23·0	+ 8·3		

* knots—westerly positive

basic flow pattern, at least at a particular longitude.

That such year to year variations in the strength of upper winds in the Australian tropics and subtropics have an important effect on rainfall was shown by Kraus (1954), who pointed out that monsoon rainfall is defective when the upper westerlies are stronger than usual in low latitudes; this is attributed to subsidence on the equatorward side of the jetstream, and to restriction of convective cloud development by strong vertical shear. Kraus's upper air observations were for spring and autumn using higher-latitude stations (Townsville and Brisbane). A similar effect can be demonstrated for lower latitude in summer, for the actual monsoonal region. Table 2 sets out the average percentage departures of the monthly rainfall for Australian rainfall district 14, Northern Rivers (see Fig. 2 inset) from the *monthly* mean, against the average departures of Darwin-Alice Springs 200-mb contour height difference from the monthly mean, for November to March for 10 to 12 years. The individual values show quite a large scatter, particularly at the beginning and end of the season, as is to be expected.

4. Changes in Upper Flow in Relation to Monsoon Onset

In the Australasian region, it has been shown by Radok and Grant (*loc. cit.*), mainly using geostrophic winds, that there is a shift in the latitude of the main jet-stream in late spring or early summer, from about 25° to 40°S, although a secondary zonal wind maximum may in some years persist in low latitudes. Another feature of the summer flow is the establishment of a ridge or a closed high at 200 mb over the Australian continent in certain years. Both these effects result in easterlies or reduce westerlies in the tropics and subtropics.

(a) The tropical region

The Darwin rawin observations show that there is a marked and often abrupt

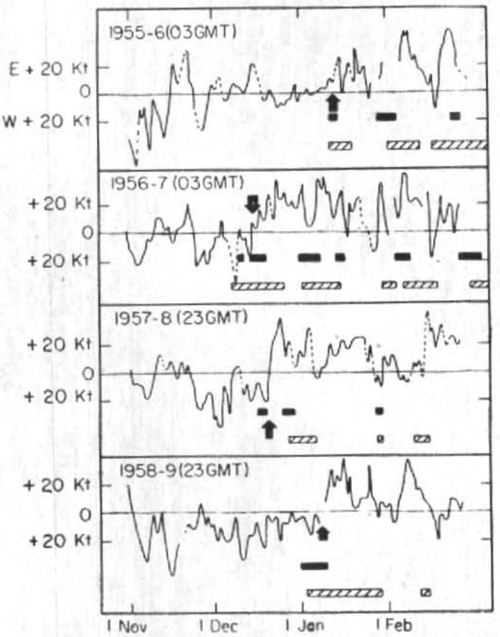

Fig. 5. Daily values of Darwin 45,000 ft zonal wind components (kt., W'lies + ve)

Interpolated values indicated by dashed lines, rain spells indicated by filled blocks, west wind spells by hatched blocks

increase (regarding east winds as positive) in the zonal component, at levels of forty to fifty thousand feet (200 to 125 mb) at or about the time of monsoon onset. (For brevity, both at Darwin and other stations this phenomenon will be referred to in future as "the transition", and the flow before as westerly and afterwards as easterly). The subsequent easterly flow does not necessarily persist throughout the season, but lasts for at least a month. These transitions are illustrated in Fig. 5 which gives the daily values of the zonal component at 45,000 ft (150 mb) at Darwin for the four seasons considered, and also the spells of heavy rain and west wind. Approximate dates for the transition are set out in Table 3. A minimum of twenty days has been taken for the easterly flow subsequent to the transition (although there may be brief interruptions of one or two days), and the values of the 20-day means before and after it are also set out in this table, indicating a change in mean of

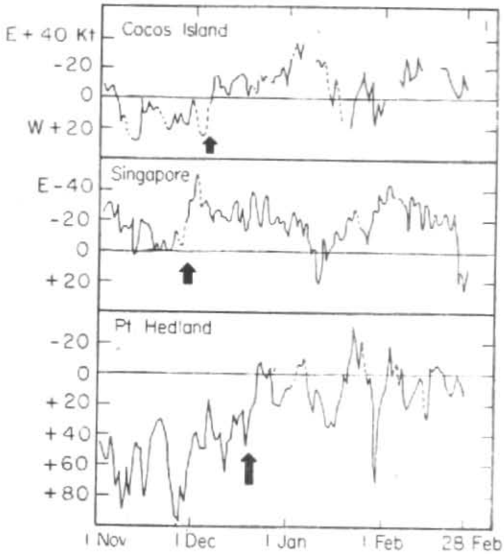

Fig. 6. 40,000 ft zonal wind components 1956-57 season (03 GMT)

the order of 20 knots. (The abruptness of the transition should not be judged from the dates in this Table, which determine the period of the twenty day means). Since a change in regime—although not necessarily in *seasonal* regime—is considered, it is desirable to confirm it while excluding particular disturbances associated with the transition itself. "Student's" *t*-test, with due allowance for auto-correlation, has therefore been applied to testing the significance of the difference between the 20—day means prior to, and eleven to thirty days after the transition, for three of the four seasons (the 1955-6 season could not be used due to the absence of observations for seven consecutive days). The details of the application of this test are left to an appendix; the changes in mean, of which the smallest is 14 kt , are all significant at the one per cent level. Of course, this significance level is not strictly applicable since the test has been applied to *selected* and not random samples, but it is indicative of a considerable degree of significance.

Similar transitions may be observed at other stations in the region; those mainly considered here are Singapore, Cocos Island and Port Hedland. Table 3 also gives the dates and 20-day-mean values for such transitions at these stations for the 200-mb level.* At Singapore, the occurrence of westerlies or weak easterlies is an anomaly, and there is not a transition from a westerly regime to an easterly, but rather a resumption of the normal seasonal flow. Transitions at this station are roughly contemporary with those at Cocos Island, and precede those at Darwin by two to three weeks. At Port Hedland the changes are contemporary with or slightly earlier than those at Darwin.

The readjustment of the tropical atmosphere is by no means as simple as an immediate change from one regime to another. In some years and at some stations (for instance Darwin in 1955/6) there is evidence of a change from a strongly disturbed flow to a much steadier one, sometimes with little change in mean. The Cocos Island transition in 1958/9 appears to have been of this type.

As an example of the large area the transition may cover, daily values of zonal component at Cocos Island, Port Hedland and Singapore at 200 mb for the 1956/7 season are shown in Fig. 6. Changes associated with the transition may also be observed at other stations. At Lae, in the 1956/7 season, although observations are missing for much of December, there is a marked difference between

*The level at which the greatest change takes place, will vary with the location of the station relative to the major upper streams, and with variations in these. The upper westerlies normally reach their maximum speed and greatest equatorward extent at 200 mb, while the easterly jet is located at 125 mb, *cf.* Fig. 3. The 200-mb level has the advantages of comparison with jet stream changes, to be discussed afterwards, and of few missing observations. It is usually adequate to represent the transition, because the flow is fairly well correlated with that in the ten thousand feet above.

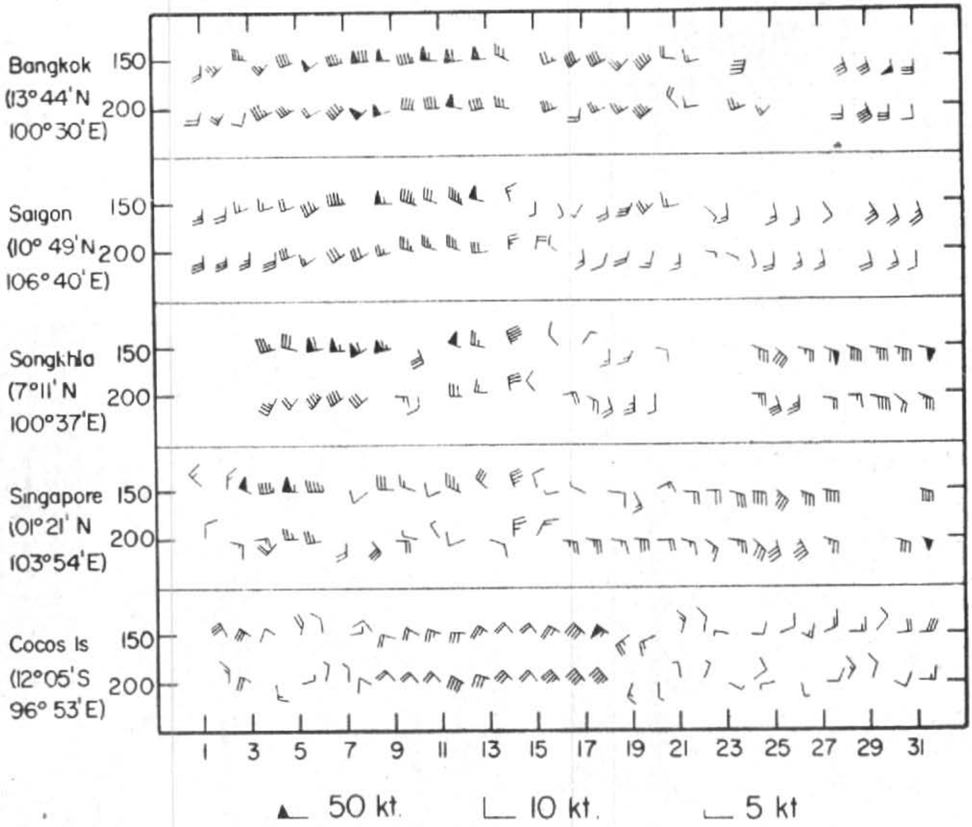

Fig. 7. Time cross-section of 200 and 150 mb winds, 00 GMT, December 1958, 105°E

the November winds mostly westerlies, and those at the end of December and during January, when strong easterlies prevail.

In the two other seasons, the prevailing upper easterlies became considerably stronger for a period of two or three weeks, at about the same time or slightly after the transition at Darwin.

It appears from consideration of the observations at 105°E, that changes from westerlies to easterlies such as those considered here, may also extend well into the Northern Hemisphere, at least to 10°N lat. As an example, time variations of the 200 - and 150-mb winds at 00 GMT during December 1958 (taken from the IGY microcards) are shown in Fig. 7, at stations from 12°S to 14°N. This shows the abrupt replacement of westerly flow by a south to east stream about the middle of the month, the change being particularly marked at the lower latitudes.

Other parameters which might have more dynamic significance have also been investigated, to see whether they might provide a clearer indication of the change from winter to summer conditions. These were, the vertical shear between 300 and 200 mb, and the shear of the zonal wind at 200 mb between Singapore and Cocos Island. The former shows a tendency to change from positive (westerlies increasing or easterlies decreasing with height) to negative shear at or about the time of transition, but the change is less marked and definite. The latter may show a decline associated with transition, but this is also less marked, the easterlies being stronger on the average at Singapore than at Cocos throughout.

On the whole, the time intervals between monsoonal phenomena and the transition show less variability when the rain onset is considered; this is preceded by the transition by about two weeks at Singapore and Cocos Island, while at Darwin and Port Hedland the changes are roughly contemporary.

(b) The subtropical jetstream

The monsoon onset is usually associated with a poleward shift or weakening of the southern subtropical jetstream; in different years this may be the main jetstream itself, or the secondary maximum sometimes found in low latitudes during summer. Variations at Port Hedland (see Table 3 and Fig. 6) are related to the position and strength of the jet; its behaviour at 135°E has also been examined, as determined from *zonal* winds derived from the 200-mb contour-isotach charts of the Australian Bureau of Meteorology. During these four years, in November and part or all of December a jet was located at an average latitude of about 25°—30°S. Occasional interruptions to this flow occurred, but were usually of short duration; they were associated with well-developed upper ridges or anticyclones. These may give rise to easterlies in low latitudes, but quite frequently such easterlies are confined to the outer tropics and subtropics, while a low-latitude trough results in westerlies in 10—15°S. Near monsoon onset, the jet at 135°E shifted rapidly to the latitude of Adelaide (35°S) and then usually maintained its summer position south of the continent for some time. The abnormality of the 1956/7 season may partly be associated with the rather far southward position of the jet, about 32°S, prior to its shift. Dates of the jetstream shift are also given in Table 3. It should be emphasised that the jet may return to low latitudes some time after; in India also, strong westerlies may be found in low latitudes for short periods after the major jetstream shift occurs (Koteswaram 1958). The month of January 1958 must be considered abnormal; there was a persistent and strong low-latitude jet for most of the month, after it has temporarily retreated at the end of December. There is some evidence (Murray 1960) that this month was abnormal in other regions; it is hoped to deal more fully with this elsewhere.

As further illustration of the somewhat spectacular nature the change may have on occasions, in Fig. 8a and 8b are presented 5-day mean cross-sections of zonal wind and potential temperature for the periods 16—20 December and 22—26 December 1957. The zonal components are derived from observed winds. There are also large changes in the meridional components (not reproduced here) but these are more difficult to interpret, particularly in a cross-section at one longitude. It might be expected that there would be a decrease in the Southern Hemisphere Hadley circulation, and an increase in the Northern one, with monsoon onset, expressed as reduced northerly or increased southerly components at high levels. However such a result could only be expected to be established on space—and time—averages as such changes would be swamped by those due to synoptic disturbances.

5. Discussion

The results of the preceding sections may be summarised as follows—The monsoon in the North Australian region consists of spells of heavy rains, and of moderate westerly winds in the low levels, which occur mainly in January and February. In the upper troposphere there is in low latitudes (but not necessarily on the equator) an increase in easterly component from November to February. This is the result

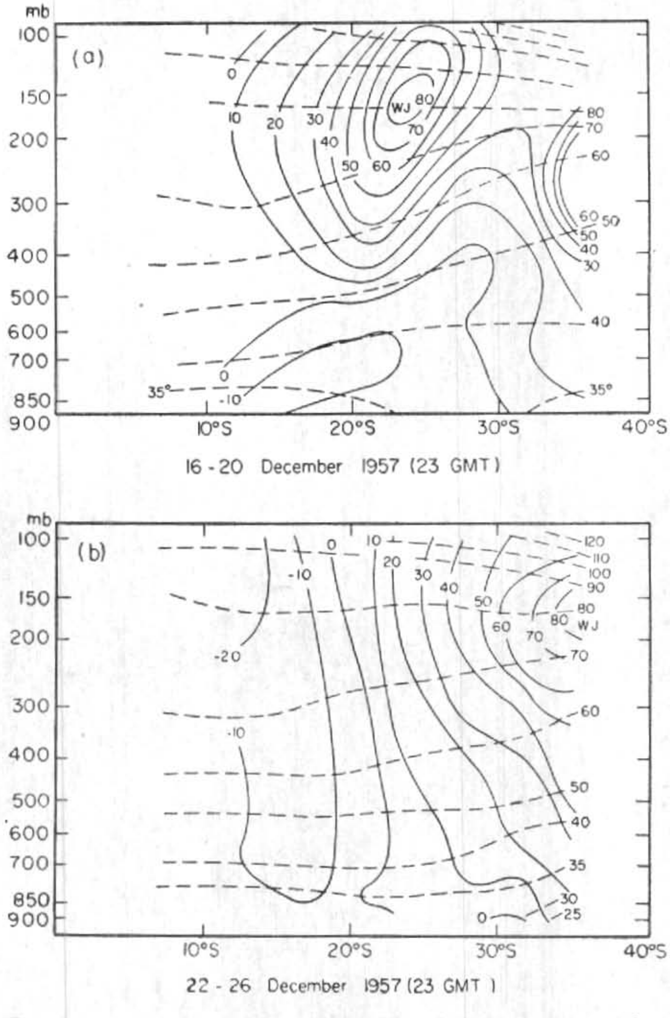

Fig. 8. Five-day mean cross-sections of observed zonal flow and of potential temperature at 135°E

Solid lines—zonal flow (knots, westerly positive)
Dashed lines— potential temperature °C

of more frequently occurring and longer lasting periods of easterlies, and is not necessarily the establishment of a steady easterly regime, as occurs over Asia. The onset of the monsoon in the Darwin region is preceded in the East Indian Ocean, and accompanied (or immediately followed) in the area itself, by the beginning of one of these periods of easterlies; it is also associated with an abrupt poleward shift of the Southern Hemisphere subtropical jetstream. These widespread changes can extend into the Northern Hemisphere.

Except that changes in upper winds are less subject to local influences, these transitions are not of more use as *predictors* of monsoon onset than flow changes near the surface, since they are approximately contemporary with these. At Cocos Island, it is true, there is only a slight weakening of the trades after the transition; but the

Cocos and Singapore changes would occur about the same time as the monsoon onset in Java. The same holds for Aden, where the upper easterlies set in at about the same time as the southwest monsoon reaches the corresponding latitude in the western Arabian Sea. What they do indicate is that the monsoon bursts do not occur just simply as a surge of colder air from the winter hemisphere, but as a result of dynamic effects through a large depth of atmosphere.

The formation of these upper easterlies appears to be due to development rather than to the movement of individual eddies from region to region, (these may be connected with the transition itself), or to the upstream or downstream movement of an established jet. Thus if strong upper easterlies occur in the Darwin region in spring, they are usually associated with the passage of individual rapidly-moving anticyclonic eddies to the south, and are of relatively shorter duration, so that a trough-ridge pattern of large amplitude obtains. During the monsoon season it would seem rather that there is a tendency for the upper subtropical anticyclone to expand with southward movement of the "subtropical ridge"; this appears to occur earlier in the West Indian Ocean, then further east. The role of individual disturbances superimposed on this large-scale process will of course be important; by analogy with the Indian monsoon, one would expect monsoon rainfall and disturbances to be associated with troughs in the upper easterlies and with individual jet maxima (Koteswaram and George 1958, Srinivasan 1960) but that the existence of a persistent strong easterly jet would inhibit rainfall. Thus the climatological relationship between easterlies and rainfall does not imply a one-to-one correspondence in the short-term situation. The effect of such upper disturbances in the Australian region have not been examined fully, due largely to lack of data from the surrounding oceans. Their importance is undoubtedly great; for instance in the latest season considered, although the westerly jet stream had shifted south at 120°E, in the longitude of Darwin it still remained in relatively low latitudes; the monsoon onset rainfall was apparently associated with the upper divergence in the north to northwest flow of the northeast quadrant of a cut-off upper cyclone. The easterlies did not set in until a week later in 135°E longitude.

The present study, concerned as it is with only a limited number of years, needs several more for the confirmation of the observations and ideas presented. In particular relationships with equatorial and trans-equatorial flow need further study. It will be seen for instance from Table 3 that no transition occurred at Singapore in 1955-6 at 200 mb, although such a phenomenon occurred at Cocos. A point of special interest would be the connection with the behaviour of the westerly jetstream south of the Himalayas. As this may be established there in October (Staff Members Acadamia Sinica, *loc. cit.*) any weakening of the equatorial upper easterlies would not be associated directly with this event—in fact the converse could be the case (Ramage 1952). It appears more probable that there is a disruption of the Northern Hemisphere subtropical ridge with a strong upper trough extending into very low latitudes, concurrent with a similar process in the Southern Hemisphere. [There may be a tendency for this to occur as a November singularity, since this is the *only* month in which a mean west wind occurs at 10 km at Djakarta (Braak 1929)]. This is then followed by development, centred on latitudes 10—20°, of anticyclonic patterns in the 200—100 mb layers. This occurs in both hemispheres simultaneously on approximately the same longitude, with the re-establishment or establishment of the easterlies. It is clear that the study of events in both hemispheres is fundamental for a full understanding of monsoon behaviour.

6. Acknowledgements

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APPENDIX

Application of "Student's" t-test to the Darwin upper winds

The application of the t-test requires that the observations are drawn from a population that is approximately normal. It is generally accepted that with only a few exceptions at particular levels and periods, the zonal components of winds in the free atmosphere are approximately normally distributed, and this has been demonstrated even for an equatorial station such as Singapore (Scott 1957). However the test as usually applied requires that the observations be independent.

An expression for the standard deviation of the mean in an autocorrelated series is given by Lewis and McIntosh (1952).

This is:

$$\sigma^2_n = \frac{\sigma^2}{n}\left[1 + \frac{2}{n}\left\{(n-1)r_1 + (n-2)r_2 + \ldots\ldots\ldots\ldots\ldots + r_{n-1}\right\}\right]$$

where σ_n is the standard deviation of the mean of n observations, σ the population standard deviation, n the number of observations and r_p is the autocorrelation with lag p. The coefficient of σ^2/n is the "equivalent number of repetitions", and dividing this into the total number of observations gives the number of independent observations.

The autocorrelations for one- and two-day lags have been determined for the forty days before and forty days after the transition, for three seasons, and have been combined using Fisher's z-transformation. This gives autocorrelation coefficients of 0·55 and 0·32 respectively; subsequent coefficients have been obtained by assuming $r_p = r_1^p$. Thus there are approximately seven independent observations for twenty consecutive daily observations, and the t-test for difference between means is entered with twelve degrees of freedom.

As mentioned in Section 4, there is some uncertainty about the *interpretation* of significance values so determined, since a significance figure of one per cent implies that in *random* samples such differences in mean would be found on only one per cent of occasions. Since two selected samples are compared, the difference will not be as significant as implied.