VARIATIONS IN THE HIGH TROPOSPHERIC MEAN FLOW OVER AUSTRALIA AND NEW ZEALAND

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ABSTRACT

As first step in an investigation of changes in the high-level circulation of the southern hemisphere, more than 18,000 radiosonde flights have been used to construct a three-year series of monthly mean cross-sections for the eastern Australian sector and to draw, with their help, monthly mean 200-millibar charts for the entire region of Australia and New Zealand, by methods suited to its sparse upper-air station network. For eleven of the 36 months, the cross sections could be extended as far as the Antarctic coast to show details of a high-latitude jet stream. The 200-mb charts reveal distinct deviations from zonal flow, but only a few of these seem clearly linked to certain seasons or regions. Transitions from summer to winter flow-patterns occurred as a rule abruptly, and on several occasions coincided with the opposite transition in the zonal mean flow of the northern hemisphere.

1. Introduction

This study arose from the first stage of a research project into possibilities for long-range forecasting by way of the southern-hemisphere general circulation. The background and basic ideas of the project have been given in detail elsewhere (Radok, 1954). Briefly, the approach chosen uses the fact that the synoptic time- and space-scales are such as to make seasonal weather conditions depend on the characteristics and behavior of a comparatively small number of eddies, each of which can be studied individually, in contrast to those of a turbulent process in the usual sense of the term. From this point of view, the state of the circulation during a period must be described by time sequences of the values of a set of descriptive eddy parameters; and a steady circulation state is indicated when these values are in statistical "control" (Shewhart, 1931). The choice of suitable parameters is dictated by short-range synoptic experience, which in this approach would have to specify the weather likely to accompany the average eddy. It follows that consideration must be given not only to the surface pressure field but also to the upper flow conditions, especially at the level of the subtropical jet stream, which in the southern hemisphere dominates most land areas. Thus, the first stage of the project came to be devoted to a study of the variations which occur in the high tropospheric circulation of the southern hemisphere.

Due to the uneven distribution of aerological stations, it proved desirable to consider separately one region which has a reasonable cover of stations and the remainder of the hemisphere with (at the time) fewer than half a dozen stations in all. The present article deals exclusively with the former, the region of Australia and New Zealand (abbreviated to ANZ region in the following), covering some 80 deg long and 40 deg lat. Even in this region, details of the mean flow between 500 and 100 mb, and particularly of the velocity maximum near the 200-mb level, could only be established by special methods. These methods are discussed in the next section, while the remainder of the article gives details of the circulation during a three-year period, from September 1949 to August 1952. The emphasis throughout is on subtropical and higher latitudes, where the geostrophic assumption largely accounts for observed winds.

2. Method of analysis

Fig. 1 shows the network of upper-air stations operating in the ANZ region during all or part of the three-year period to be considered. At the time, most of these were radiosonde stations only. Extensive high-level wind data existed for the eastern boundary of the area, where at first two and later three radar wind-stations were in operation, and also in the northwest corner of Australia, where predominantly clear condi-

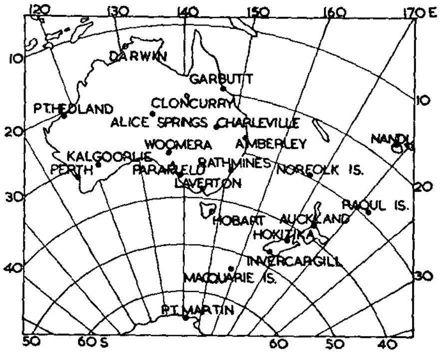

FIG. 1. Radiosonde stations used for cross sections and charts.

tions permitted the Port Hedland radiosonde to be followed regularly by theodolite to great heights. However, generally speaking, high-level wind data were scarce during the period in question, so that the analysis had to be based on upper temperatures and the geostrophic relation.

A basic zonal current is then determined, strictly speaking, by mean contour heights taken around latitude circles — an ideal situation as yet unattainable for the southern hemisphere. Even a substitute, the average of several meridional height profiles, faces great difficulties; with the possible exception of 170°E, no single longitude carries a sufficient number of stations. In these circumstances, the nearest approach to some sort of basic current seemed to be provided by a meridional cross-section incorporating all radiosonde stations in an extensive area such as eastern Australia. The construction of such a cross section amounts to a spatial averaging on top of the usual one in time, and offers little difficulty as long as the distortions of the mean zonal current have the character of wave-like meridional displacements of isobaric and isentropic surfaces without appreciable changes in their slopes. This was found to be the rule during the period investigated.

The mean zonal winds for the eastern Australian sector were determined from the geostrophic zonal winds at the 500-mb level (as given by the 500-mb mean height profile for the sector) and the thermal winds in the layers between isentropes 5K apart, by means of a modified version of Matthewman's (1950) technique especially suited to meridional cross-sections (Radok and Grant, 1951). This procedure has the advantage that the large velocities of the upper troposphere are obtained as sums of numbers of small increments, the errors in which will compensate one another to some extent.

The geostrophic winds thus obtained for the 200-mb level were next integrated with respect to the meridional cross-section coordinate, which has the form

$$y = c(1 - \cos \varphi),$$

where c is a constant, and φ is the latitude. The geostrophic relation can then be written

$$U = -(cg/2\omega R)(dh/dy)_p,$$

where g and ω have their usual meaning, R is the diameter of the earth, and h is the height of the 200-mb surface in the present context; hence,

$$h_0 - h = (2\omega R/cg) \int_{y_0}^{y(\varphi)} u\, dy.$$

Here h_0 and h represent the heights of the 200-mb surface at the northern boundary of the area considered (15°S, $y = y_0$) and at latitude φ, respectively, and the integration is performed along the 200-mb surface.

This operation provided space-time mean meridional height profiles of the 200-mb surface which were used as standards of reference. For each radiosonde station, the differences between the observed 200-mb mean heights and the standard heights for the station latitude defined a set of height deviations. Precise comparisons between stations can be made in terms of these deviations, since now the small height changes with longitude are no longer swamped by the much larger variations with latitude. Moreover, from several height deviations for approximately the same latitude, a meridional profile can be constructed which, added to the standard height profile, will produce a distorted profile valid for the longitude in question. Fig. 2 shows a set of such distorted profiles, together with the relevant standard profile, based on all radiosonde stations between 130°E and 160°E. From such profiles, the latitudes of intersection with different 200-ft contours were read off and used to draw 200-mb mean contours for the entire ANZ region.

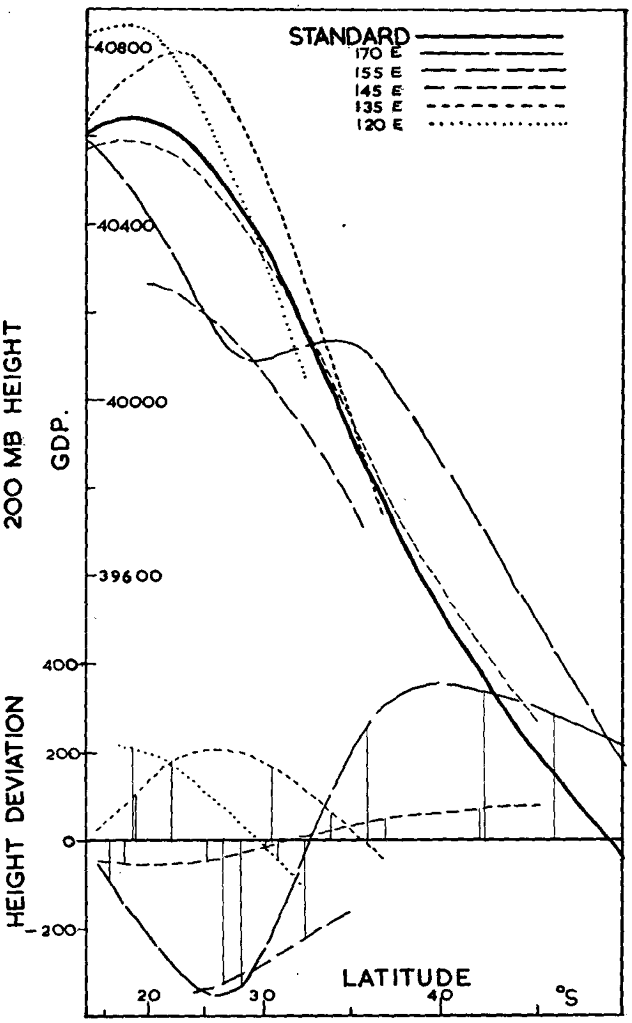

FIG. 2. Standard and distorted 200-mb height profiles for first half of January 1951. Each thin vertical line represents a difference between station mean height and standard profile height for station latitude. Heights in geopotential feet.

This procedure uses the available radiosonde observations to the full and substitutes the characteristics of the basic current where no other information exists. On the whole, this must lead to less complex flow patterns than those prevailing in reality. A test of the charts by means of observed winds remained inconclusive, because the latter were mostly far less numerous than the temperature observations. This is shown in table 1, which gives the total numbers of observations at the 200-mb level for each station. In these circumstances, the resultant wind vectors provide an independent alternative picture of the wind field (except at the eastern boundary, where the contour directions and spacings were adjusted to agree with the winds observed in great detail at Nandi, Auckland and Invercargill).

The period of averaging was chosen as short as practicable, half a month. This helped to preserve details of major disturbances — whose life time is of the same order of magnitude — while ensuring sufficient observations from each station for reasonably stable temperature and height averages. By an averaging of pairs of half-monthly cross-sections and charts, the final series of independent monthly mean cross-sections and 200-mb charts was obtained. Twice as large a series of overlapping monthly mean charts could have been constructed, but at the cost of creating a spurious continuity in time which conflicts with the essential nature of time averages. This is well illustrated by the fact, easily verified, that a rate of change (*e.g.*, a velocity or a height tendency) computed from two means each covering n days and overlapping by m days ($n > m$), which *appears* to relate events n-m days apart, represents in reality the rate of change between two *independent* means each covering n-m days and *centered n days apart*, whatever the value of m.

Table 1. Numbers of radiosonde and wind observations for 200-mb level used in construction of cross sections and charts.

Station	No. of radiosonde observations	No. of wind observations
Port Hedland	720	526
Cloncurry	950	81
Alice Springs	961	292
Kalgoorlie	766	61
Woomera	962	304
Rathmines	969	104
Laverton	895	350
Nandi	856	913
Auckland	992	1040
Invercargill	896	346
Port Martin	84	26
Darwin	931	—
Garbutt	957	—
Charleville	928	—
Amberley	859	—
Perth	1037	—
Parafield	1012	—
Hobart	985	—
Macquarie Is.	915	—
Norfolk Is.	768	—
Hokitika	980	—
Raoul Is.	100	—

The present series of independent successive mean cross-sections and 200-mb charts appears to be the first of its kind to have been constructed for a part of the southern hemisphere, and its main features will now be discussed.

3. Some features of the mean flow

The monthly mean flow patterns of the period September 1949 to August 1952 are given, by seasons, in figs. 3 to 6. Additional features of the zonal flow over eastern Australia are illustrated on the left of each 200-mb chart by a simplified version of the basic cross-section for the same month. Due to the use of the geostrophic and thermal wind relations, the patterns of the isotherms or isentropes and of the zonal velocity isopleths are completely equivalent; therefore, only the latter have been retained, as showing clearly changes in the strength and the latitude of the subtropical jet stream.

These changes would have emerged even more clearly from charts of height and velocity anomalies. However, for such anomalies to have any meaning, they must be derived from comparisons with genuinely normal flow conditions. For the ANZ region, these are as yet unknown, due to the different lengths of record for the different stations. While for a number of these the radiosonde data go back to 1943, some of the most important stations had only just come into existence in the spring of 1949 (Hobart and Kalgoorlie) or did not start operating until well inside the period here considered (Invercargill, January 1950; Norfolk Island, June 1950; Port Hedland, July 1951). In these circumstances, it seemed preferable to rely on direct comparisons between the contour charts for each season, which in any case contain a multiplicity of information not visible in any anomaly representation. In the cross sections, on the other hand, the approach to normal conditions would presumably be accelerated by the averaging over both space and time, so that anomalies based on three-year averages may be of some interest. Therefore, the regions in which the monthly mean zonal velocity exceeded the three-year average for the same month have been marked by dots in the cross sections of figs. 3 to 6.

It is at once evident from the charts that strictly zonal mean flow was the exception rather than the rule during the period covered. Objectively, the distortion of the flow is measured by the local height deviations (*cf.* section 2), each of which would be small or zero for zonal flow. The root-mean-square height deviation for the 18 stations north of latitude 50°S, within sampling limits, was found to be the same for each season, 100 ft. This seems, at first sight, in conflict with the straighter flow patterns during the winter half of the year; but it must be remembered that, with the steeper gradients then prevailing, the

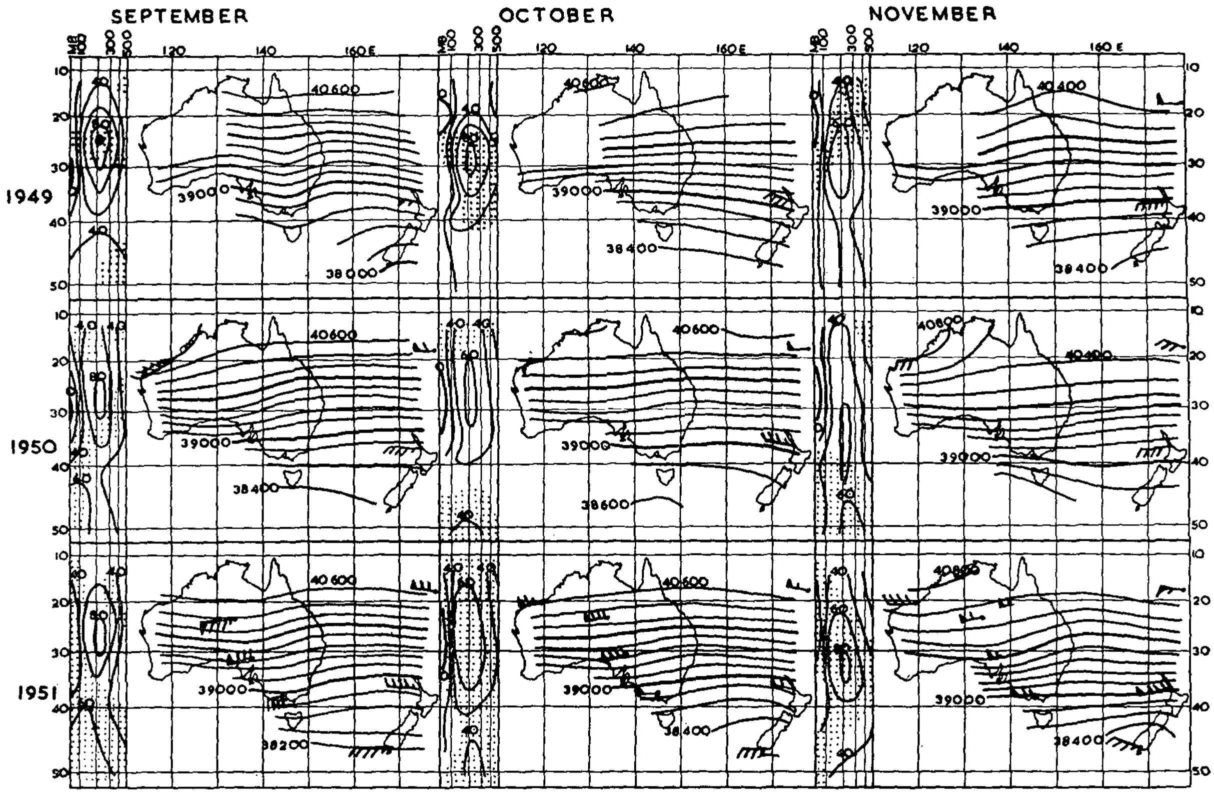

FIG. 3. Monthly mean 200-mb charts for spring, 1949–1951. Zonal velocity (mi/hr) cross-section on left of each chart approximates average conditions between 130 and 160°E (eastern Australian sector). Arrows give observed resultant winds. Dots mark regions with velocities above 3-year average for month.

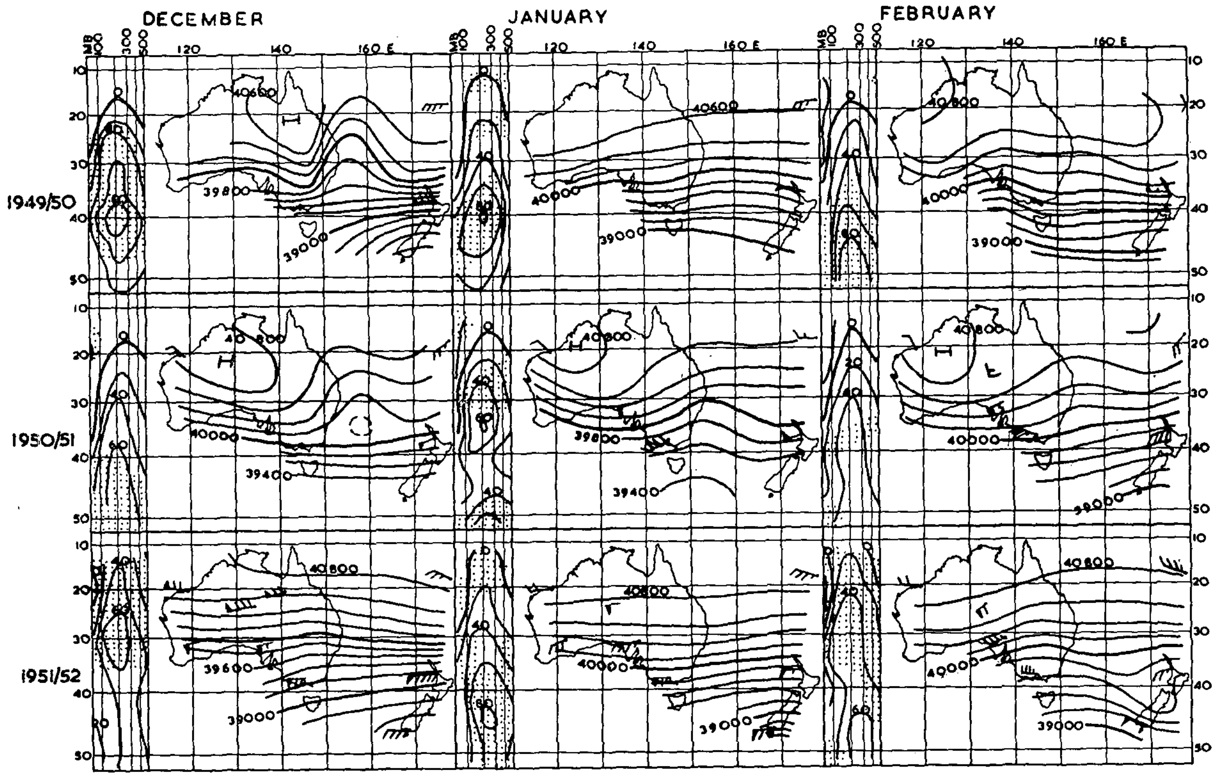

FIG. 4. Same as fig. 3, but for summer, 1949–1950 to 1951–1952.

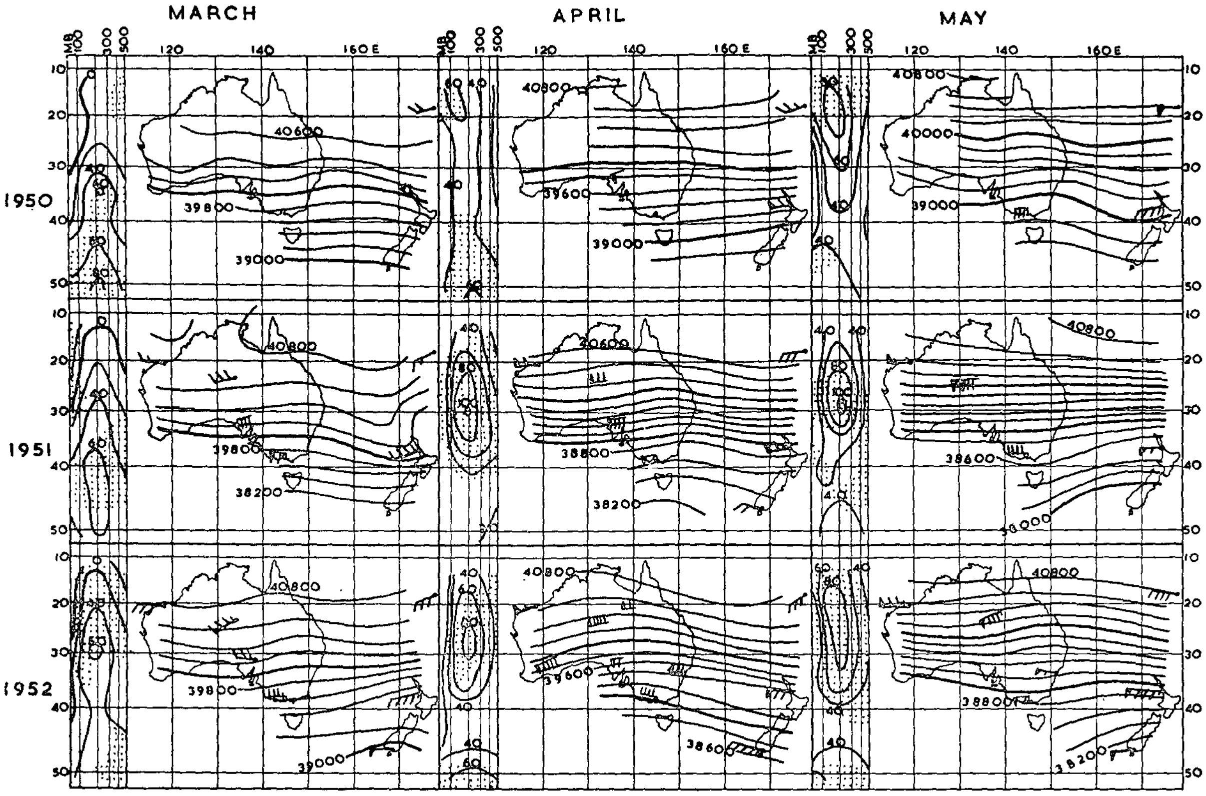

Fig. 5. Same as fig. 3, but for autumn, 1950–1952.

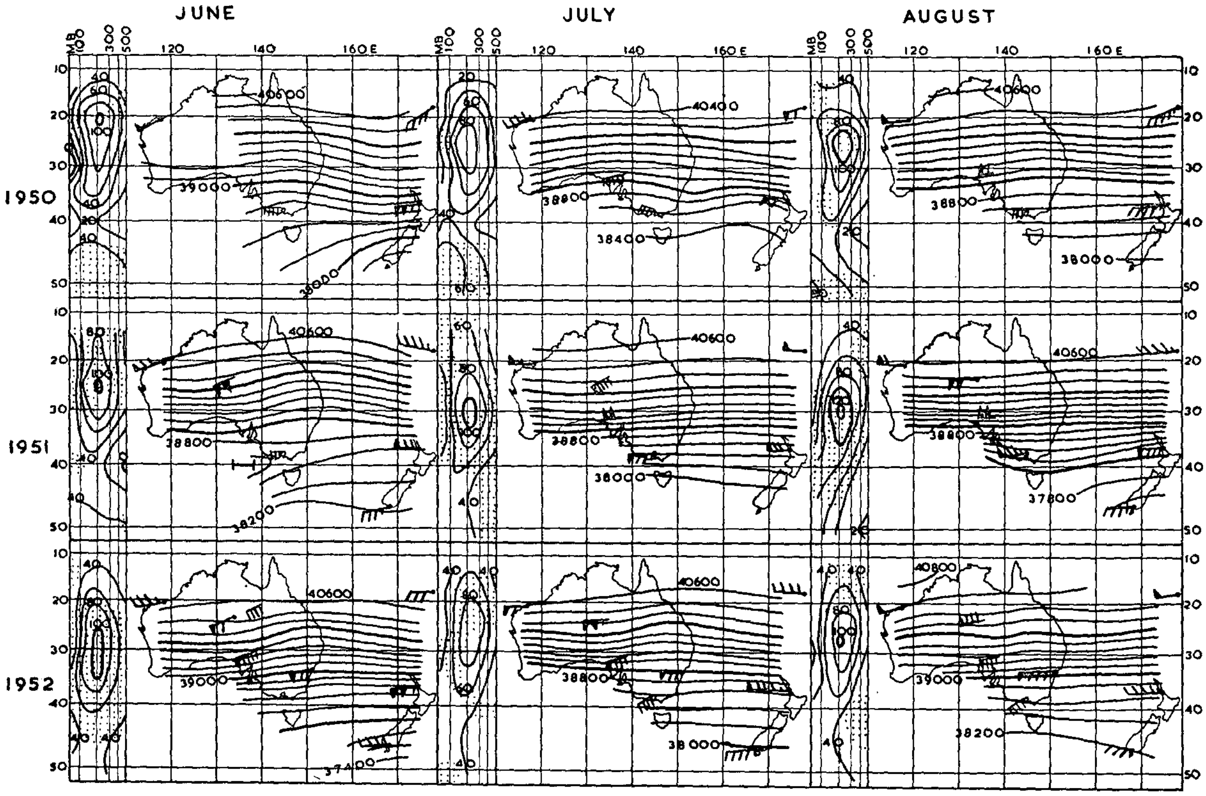

Fig. 6. Same as fig. 3, but for winter, 1950–1952.

same deviation from zonality will produce much greater height deviations than in summer.

The most notable individual chart features are closed highs which occurred in a number of summer months somewhere over the Australian continent. By contrast, troughs and ridges are found throughout the year and without clear preference for any particular region. There are also regions of slack gradients in all seasons, suggesting confluence-diffluence patterns or "splits," and these seem to have occurred mainly just south of the continent or near New Zealand. A particularly marked split persisted just east of New Zealand during the greater part of autumn 1952; fig. 7, which gives the half-monthly mean charts from the end of February to the beginning of May 1952, demonstrates the continuous existence of this split also on a shorter time scale. It is suggestive, in this connection, that the region east of New Zealand is frequently the seat of blocking anticyclones (Kerr, 1955) which also occur south of the Australian continent, especially in association with upper cut-off type depressions over New South Wales (the so-called east-coast cyclones, *cf.* Kraus, 1954). However, possible links between persistent anticyclones and individual splits in the upper westerlies remain to be confirmed by a study of the surface-pressure conditions during the same three-year period.

In the cross sections, the corresponding feature is a velocity minimum south of the continent which has its greatest prominence in winter and was noted already in the first seasonal mean cross section for eastern Australia (Loewe and Radok, 1950a). This minimum hints at a second winter jet-stream in high latitudes. The first details of such an Antarctic jet were revealed by upper-air observations at Port Martin (Prudhomme and Le Quinio, 1955) during the greater part of 1951. These data made it possible to extend the eastern Australian cross-sections to 67°S. Although no longer confined strictly to the ANZ area, these enlarged half-monthly mean cross-sections, in view of their special interest, have been reproduced in full (fig. 8). To supplement the information for summer, three cross-sections for January and February 1950, based on 35 radiosonde flights in the same region made from the "Commandant Charcot" by Chabasseur (*cf.* Loewe and Radok, 1950b), have also been included in fig. 8.

The series opened in April 1951, with the subtropical jet stream well established in its winter latitude and a second velocity maximum of comparable magnitude

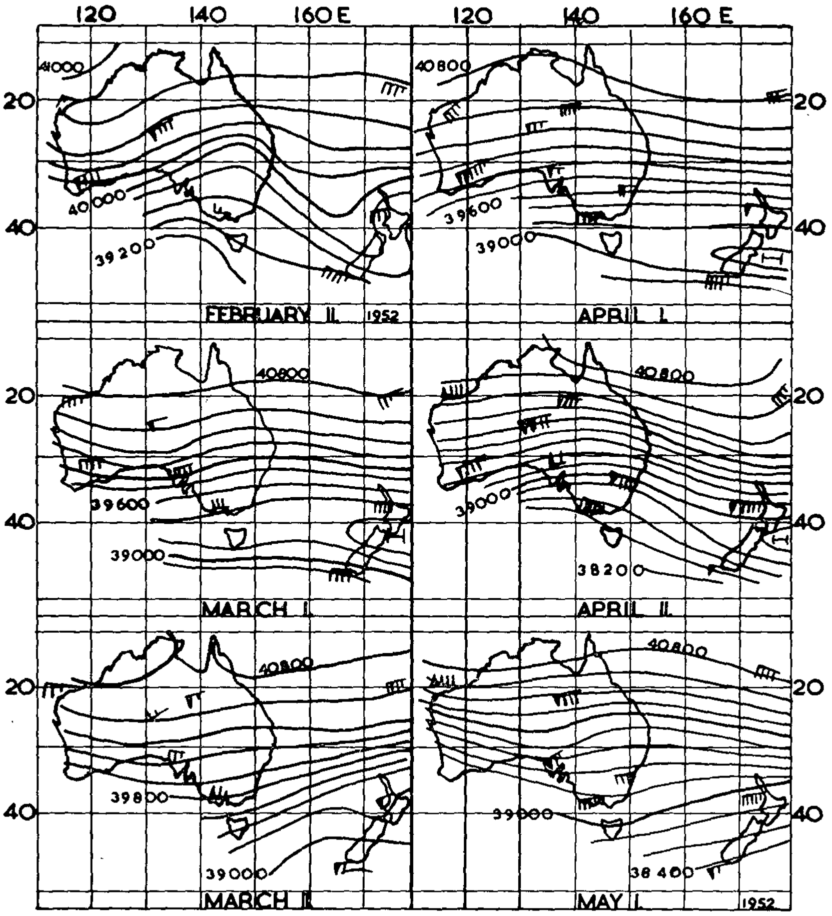

FIG. 7. Half-monthly mean 200-mb charts for autumn 1952, showing persistent diffluence region ("split") over New Zealand.

between 60 and 65°S. During the following months, the Antarctic jet stream was much weaker, until at the end of winter its intensity for a time grew far beyond that of the subtropical jet stream. Such an intensification of the high-latitude flow around the time of the equinoxes has recently been predicted by Schwerdtfeger and Prohaska (1956). The double jet pattern persisted well into the summer; this was presumably an abnormal feature (*cf.* section 4). A new type of flow, with a single strong velocity maximum at 45°S appeared at the beginning of January; the 1950 cross-sections show a variant of this with the secondary summer maximum in low latitudes, first described by Hess (1948) for the northern hemisphere.

The implications of the individual mean-flow features discussed in the foregoing depend very much on the duration of the underlying disturbances. Strong transient disturbances can affect a mean chart in the same way as weak persistent ones, but their effects on monthly weather conditions will be different. It seems likely that, in the case of transient disturbances, monthly rainfall and temperature anomalies at the best might be linked to mean flow features by statistical relations such as those derived for the United States by Klein (1949). On the other hand, under quasi-stationary flow conditions, the detailed distribution of divergence and convergence in the high-level mean flow would have considerable practical significance (Riehl *et al*, 1952). The question as to which of these alternatives is more closely realized in the data here under discussion can be decided, in first approximation, from the series of half-monthly and monthly cross-sections and charts, since a necessary (though not sufficient) condition for steady flow is that the patterns for the two halves of a month should be similar to one another and hence to the monthly mean pattern. In application of that criterion, it was found that only five of the 36 200-mb charts could possibly be regarded as steady, the most notable example being April 1952 (fig. 7). For the cross sections, fig. 8, which is fairly representative of the entire half-monthly series, demonstrates the same state of affairs; and on a larger time scale, the velocity anomalies marked by dots in figs. 3 to 6 also show little persistence from month to month. In these circumstances, it seems unlikely that rainfall and temperature anomalies could be closely associated with individual mean-flow features in this region.

In the present context, we are, however, concerned mainly with broad circulation characteristics and changes which could affect the entire hemisphere and thus might be detected even in single station records outside the ANZ region. The most important of these are the transitions from a summer to a winter type of flow or *vice versa.*

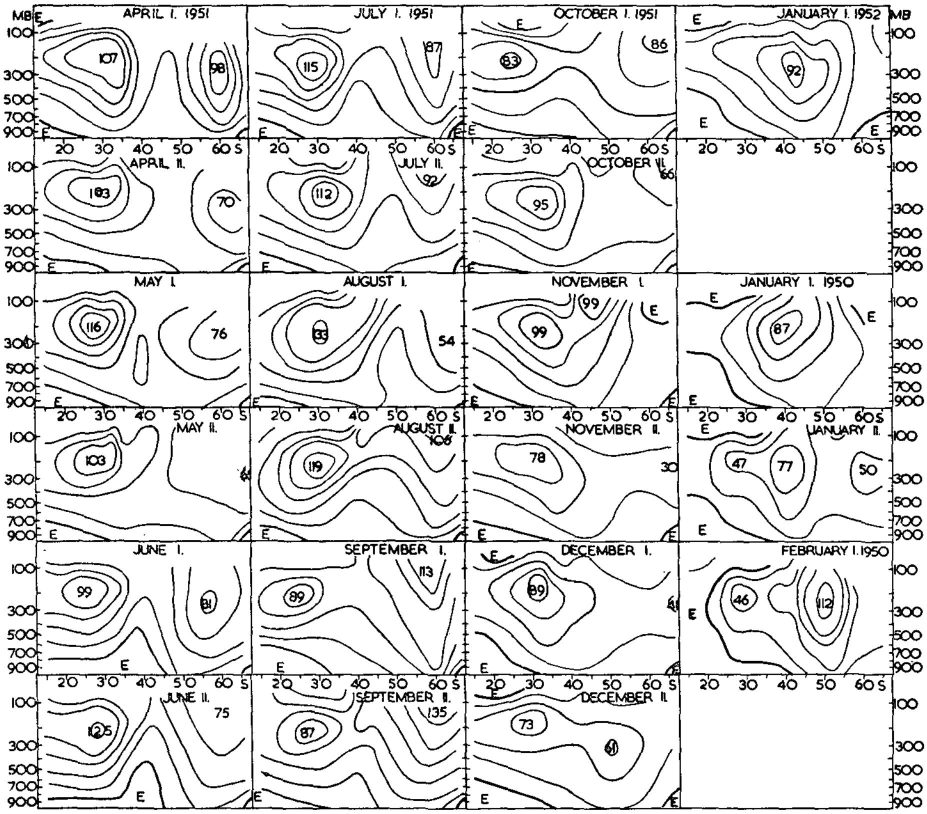

Fig. 8. Half-monthly mean zonal velocity cross-sections (20-mi/hr isotachs) for eastern Australian sector, showing antarctic jet stream. Figures give jet velocities (mi/hr).

4. Change of season in the mean flow

The winter and summer flow-patterns for the region are known, from earlier long-term mean cross-sections (Loewe and Radok, 1950a; Hutchings, 1950) and charts (Phillpot, 1951), to differ in regard to the jet-stream latitude, which ranges from 20 to 30°S in winter and from 40 to 50°S in summer. The transition from one pattern to the other will be referred to here as change of season, even though it remains open at this stage as to how far this term is justified by simultaneous changes in meteorological conditions generally.

The onset of winter took a different form in each of the three years under consideration (fig. 5). While in 1950 there were preliminary signs of a winter jet stream in the chart for March, this was followed by a featureless April pattern and an unusually low latitude of the jet in May and June. It might be mentioned, in passing, that this last anomaly arose from a series of upper lows over the east coast of Australia, which on the half-monthly scale showed up in the form of the double velocity maximum described by Gibbs (1952). In 1951, the winter jet first appeared in the April chart, whereas the following year it was clearly in evidence already in March and maintained both its location and strength during the following months.

The transitions from winter to summer might have been expected to be less clear-cut. However, in addition to the latitude shift of the jet stream, the present charts establish as a new summer feature a high or ridge over the Australian continent. Its location, and its times of formation and disappearance, again varied from year to year. Whereas the high in 1949 and 1950 was established with the first half of December, it made a brief appearance in the last summer only during the first half of February and never emerged in the monthly mean flow at all (fig. 4, bottom row).

The abnormally strong high-level westerlies over low Australian latitudes during that last summer have been noted by Kraus (1954), who held them responsible for the simultaneous failure of the monsoonal rains. The case for this view would be strengthened if the upper-flow anomaly could be shown to have been primary, *i.e.*, due to an excess production of westerly momentum during the preceding months or to a breakdown in the momentum transport to higher latitudes. In this connection, the results of eddy-flux calculations based on the Auckland wind observations (Priestley and Troup, 1954) may be quoted; they have been summarized in table 2, which compares the eddy flux of momentum during 1951 with its averages for the two preceding years.

Table 2, while in no way conclusive evidence, supports the view that the strong low-latitude westerlies during the summer of 1951–1952 could have been caused by an inadequate momentum transport during the earlier part of 1951. Similar anomalies could be established more firmly, now that calculations can be

TABLE 2. Eddy flux of momentum (10^8 dyn/cm) at Auckland. (After Priestley and Troup, 1954.)

Year	Mar.–Apr.	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.
Mean of					
1949 and 1950	3.21	0.15	1.09	1.20	1.30
1951	1.51	−0.34	−1.01	0.03*	1.62

* Doubtful.

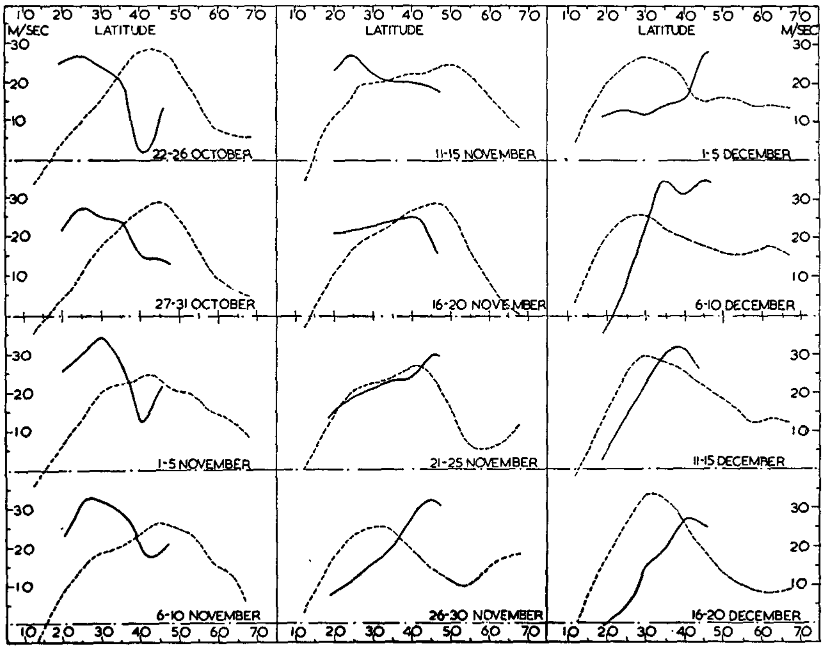

FIG. 9. Five-day mean profiles of 300-mb zonal velocities for eastern Australia (full lines) and for entire northern hemisphere (broken lines), southern spring 1950. Note latitude shift of velocity maxima during period from 16 to 25 November.

based on five radar wind-stations spread over 150 deg long near the strategic 30th parallel (Auckland, Melbourne, Perth, Amsterdam Island, Pretoria).

The magnitude of the momentum transport involved in changes of season depends on their suddenness. The half-monthly chart series still showed abrupt transitions in all cases; but with a further reduction in the time scale, the changes became gradual. An example is provided by fig. 9, in which the full lines illustrate the winter-summer change of 1950 by 5-day mean 300-mb velocity profiles for eastern Australia. The shift of the velocity maximum appears to have taken place during the pentade from 16 to 20 November in this case.

The demonstration that the jet shift in fig. 9 affected the entire southern hemisphere must be left for another context; but one striking fact about the change of November 1950 may be mentioned here, namely, that a corresponding shift in the opposite sense occurred during the following pentade, from 21 to 25 November, in the zonal mean flow computed over the entire *northern* hemisphere. This is brought out again by 5-day mean profiles of the geostrophic zonal 300-mb velocity shown as broken lines in fig. 9.[1] Further instances of the same coincidence have since been found by the junior author[2]; of five seasonal transitions studied so far, only one did not occur within the same fortnight in both hemispheres. A larger number of years will have to be studied before a linkage can be regarded as definitely established, but it seems clear from the examples found so far that at least some of the flow features of the ANZ region have more than local significance.

5. Conclusions

The high tropospheric mean flow over the region of Australia and New Zealand, while simple by northern-hemisphere standards, shows clear deviations from the zonal model often assumed for the southern hemisphere. The majority of the flow distortions observed during the period from September 1949 to August 1952 appears to have been caused by transient disturbances; the more significant remainder included anticyclones which appeared in low latitudes over the Australian continent at the beginning of two out of three summers, and diffluence-confluence patterns in preferred blocking regions south of the continent and near New Zealand. These significant distortions, and the transitions from summer- to winter-type flows and *vice versa*, may represent aspects of the southern-hemisphere general circulation; however, before they can be accepted as such, evidence for them would have to be found also outside the limited region here considered. This must be done by means of data from single stations or station pairs and will be the subject of another paper.

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[1] The writers are indebted to Dr. H. Riehl for the data from which the northern-hemisphere curves in fig. 9 were computed.

[2] While taking part in the Massachusetts Institute of Technology Foreign Students Summer Project for 1954.

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