551.510.522:
551.511.33:
551.558

ESTIMATES OF VERTICAL MOTION NEAR THE TOP OF THE BOUNDARY LAYER FOR PROJECT KOORIN

I. D. Murphy

Head Office, Bureau of Meteorology, Melbourne

(Manuscript received July 1977; revised September 1979)

ABSTRACT

A method of estimating vertical motions *that allows for diabatic heating* was applied to the Daly Waters boundary layer experiment, in order to obtain estimates of heat and mass flux transfers across the top of the boundary layer.

INTRODUCTION

Project Koorin was an observational program organised by the CSIRO Division of Atmospheric Physics and the Bureau of Meteorology to obtain detailed three-hourly data on the tropical continental boundary layer to a height of 3 km over a thirty-day period. The experiment was mounted at Daly Waters, Northern Territory (16° 16'S, 133° 55'E) during July and August 1974. It has provided a unique data set for examination of many atmospheric boundary layer problems.

Koorin, unlike its predecessor Wangara (Clarke et al. 1971), in which soundings were made at a grid of five sites, had balloon flights only at one station. Consequently vertical motions cannot be calculated directly from the experimental data as they were with Wangara. Since this information is needed in many studies of boundary layer physics, an attempt was made to estimate vertical motions at Daly Waters during the thirty days of Koorin, and this method is described here.

Of the several different approaches that could have been used, the present method was judged most appropriate for the available data as it provided a relatively simple means of estimating vertical motions from synoptic scale analyses. The basic method incorporates quasi-isentropic analysis of air motion just above the convective boundary layer to determine air trajectories, and hence relative motion between isobaric surfaces. Account is also taken of diabatic cooling due to long wave radiation by allowing motion through isentropic surfaces from one level to another. It is based on the early work of Rossby (1937) and Namias (1940) with later development *inter alios* by Danielson (1961) and Green et al. (1966) and is essentially an application of the techniques described by Cattle and Weston (1974) adapted to the Koorin situation. To do this an estimate of diabatic cooling is required. In the cases cited by Cattle and Weston (1974), a single value of 2 K per 24 hours was used; in the present analysis that value was critically re-examined.

THEORETICAL BACKGROUND

Suppose the vertical motion is required at a point D at time t in the vicinity of the isentropic surface at potential temperature θ_1. Essentially the approach by Cattle and Weston (1974) assumes that over periods of time $\Delta t/2$ the streamlines and trajectories are approximately the same. Using the streamline analysis of the θ_1 isentropic surface at time t, it is possible to estimate the pressure $p(\theta_1, t - \Delta t/2)$ assuming that the particle remained on the surface θ_1. However, if over the period Δt (centred on t), the diabatic cooling is at a rate of $\Delta\theta_R/\Delta t$, the particle will not remain on the θ_1 surface. If in fact it is on the θ_1 surface at $(t - \Delta t/2)$, it will be on the $(\theta_1 - \Delta\theta_R)$ surface at $(t + \Delta t/2)$. Then using the $(\theta_1 - \Delta\theta_R)$ isentropic analysis with the above assumptions, the pressure $p(\theta_1 - \Delta\theta_R, t + \Delta t/2)$ can be estimated. The mean vertical motion $\bar{\omega}$ over the period Δt is then approximated as:

$$\bar{\omega} = [P(\theta_1 - \Delta\theta_R, t + \Delta t/2) - P(\theta_1, t - \Delta t/2)]/\Delta t \quad \ldots 1$$

Cattle and Weston (1974) show that the error in $\bar{\omega}$ is a function of the local lapse rate within the layers near θ_1. As the lapse rate becomes more stable $\bar{\omega}$ is better estimated.

The method requires the selection of isentropic surfaces in the most stable region representative of the boundary layer. The boundary layer at Daly Waters during Koorin exhibited the classical characteristics of an inversion capped convective boundary layer with an overlying stable air mass (e.g. see Plate 1971). Consequently the isentropic surfaces at or above the inversion are suitable for this method of analysis. Examination of the isentropic time section (in Fig. 1) reveals that the most appropriate surfaces are in the range θ = 306 to 308 K.

The estimate of the cooling rate due to radiation effects is critical to the analysis. Cattle and Weston used a constant value of 2 K per day because they found, for their site in southern England during September, the day-to-day variation of diabatic cooling was an order of magnitude smaller. With the use of Koorin data, the local cooling rate (i.e. in the lowest layers of the 'free' atmosphere) was calculated each day initially for the 0900 EST ascent using a numerical method described by Myers (1966). These confirmed the relatively small day-to-day variations, compared to the actual cooling rates and the uncertainties present in their determination, and gave a value of 2 K per day due to long wave cooling. However, studies by Cox (1969), under similar synoptic conditions to those encountered during Koorin, suggest a cooling rate (the net effect of long wave cooling and short wave warming) between 1 and 1.5 K per day as more appropriate. Since meaningful resolution between isentropic surfaces less than 1 K apart is not possible, calculations for $\Delta\theta_R/\Delta t$ of 0, 1, and 2 K per day are presented for comparison.

ANALYSIS OF DATA

Isentropic analyses were made using data from the routine 2300 GMT (0830 CST) upper air network over northern Australia supplemented by the Koorin observations. The network is shown in Fig. 2. The analysis was performed for the 306 K, 307 K and 308 K surfaces. For each station with radiosonde data the pressures of these surfaces were extracted from aerological diagrams, and

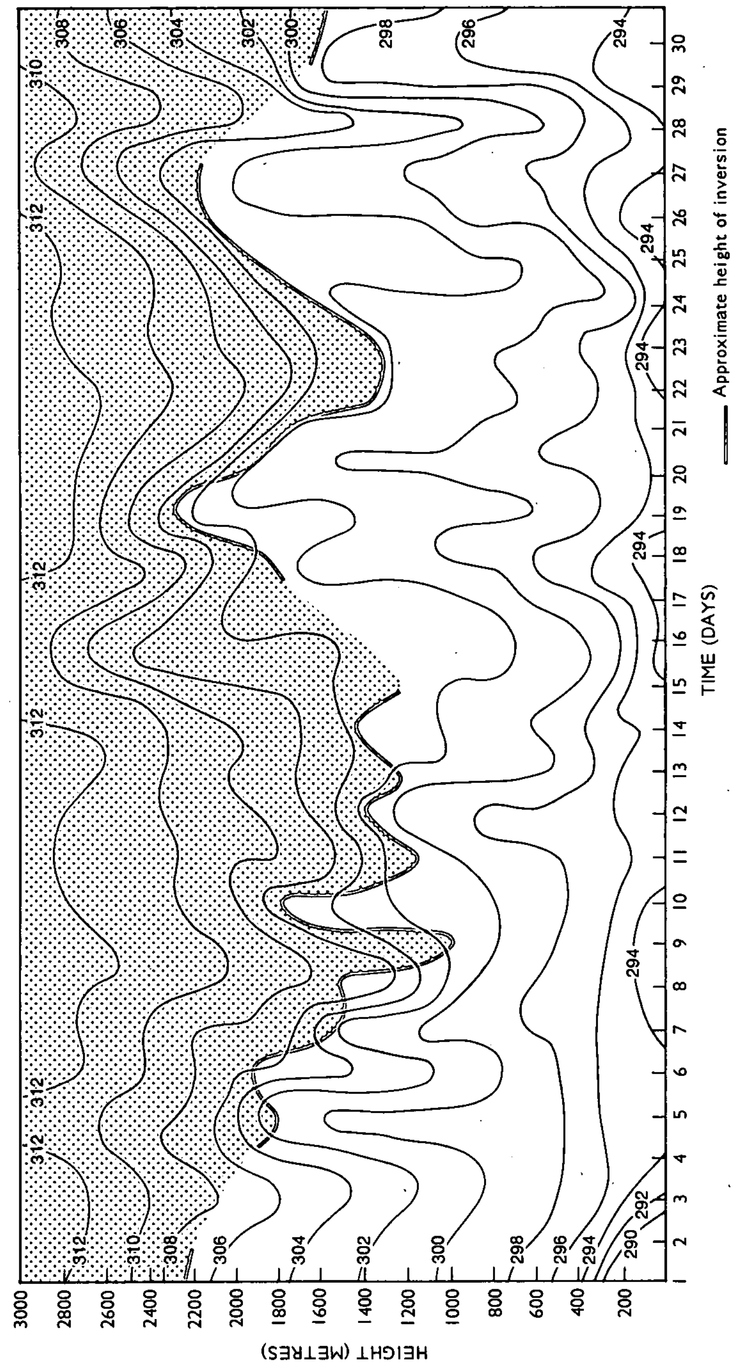

Fig. 1 Isentropic (0900 EST) time section (K), for project Koorin.

the winds were interpolated linearly from those reported at standard pressure levels. At stations without radiosonde data the pressures of the isentropic surfaces were interpolated from adjacent stations. The analysis period covered the thirty days from 15 July to 13 August 1974.

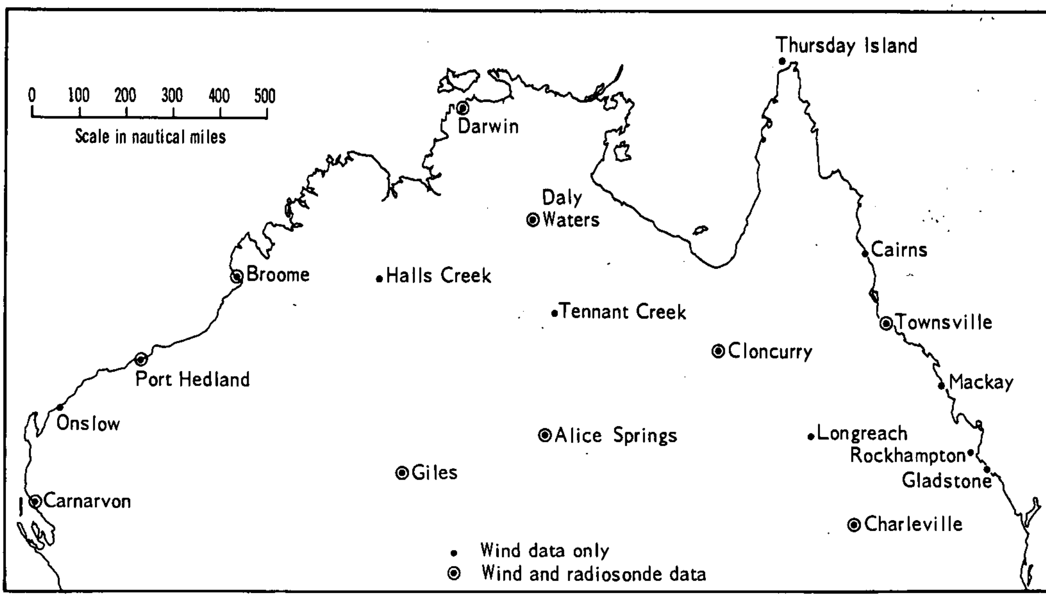

Fig. 2 Radiosonde and upper wind stations.

The isentropic analysis consisted of streamlines, isotachs and isobars. The analyses were performed manually, and as is common with such subjective approaches, the results varied with the analyst. Checks of several analyses using a second analyst gave variations in vertical motions of the order of ±10 mb per 24 hours in extreme cases. This obviously contributed to errors in the method. However, as a rule of thumb, while such differences remained less than the effect of diabatic corrections applied to vertical displacements, the results were of value.

There were serious limitations related to this data set. The primary one was the sparsity of data from stations surrounding Daly Waters in the observational network. Also, since all stations except Daly Waters and Darwin provide only one temperature sounding a day, the time period Δt had to be 24 rather than 12 hours as used by Cattle and Weston (1974), with a consequent decrease in the correlation between streamlines and particle trajectories. Lapse rates for the regions being analysed were similar to those reported by Cattle and Weston (1974), indicating an error due to this source of about ±10 mb in the pressure altitude of the isentropic surface.

In general the errors in the northern Australia data set are of a similar or smaller magnitude, except those due to less frequent soundings, when compared with those used by Cattle and Weston (1974) and would therefore fall within their root mean square error for vertical motion of ±30 mb/day.

Calculation of vertical motion assuming no diabatic heating

When the correction for diabatic cooling is not included the method is simple and can be applied to any isentropic surface. Figure 3 shows the 307 K potential temperature analysis for day 27 of Koorin (10 August 1974). At Daly Waters, marked as D on the chart, a mean 24-hour value of the vertical motion can be estimated by following the trajectory of a parcel of air on the isentropic surface:

Step 1: Using the streamlines and isotachs, the pressure level at which the parcel finds itself 12 hours upstream from Daly Waters is estimated (point A Fig. 3).

Step 2: Similarly the pressure level (marked as B on Fig. 3) at which the parcel finds itself 12 hours downstream from Daly Waters is estimated.

Step 3: The pressure difference between points A and B gives an estimate of a mean 24-hour vertical motion at Daly Waters without allowance for diabatic cooling.

Using this method for the case shown gave a mean value of approximately 40 mb/day directed downward. The mean motion was centred on the time of the working analysis, i.e. 2300 GMT.

The results of this analysis for each day of Koorin were tabulated in Table 1 for three levels, along with the surface pressure and pressure altitude of the 306, 307, and 308 K isentropic surfaces and the mean 24-hour vertical motion (A - B) for each day.

Calculation of vertical motion assuming diabatic processes

To allow for diabatic cooling step 2 in the previous example must be altered. To illustrate the approach adopted, the 307 K analysis (Fig. 3) used for the previous example, together with an assumed 24-hour cooling rate of 1 K, is used. The air parcel trajectory for the first 12 hours will be the same as that of step 1 in the previous example. The second 12 hours of the air parcel's motion will now be on the 306 K isentropic surface, and the pressure must be determined at a new point B' on this surface downstream from D as shown in Fig. 4. The mean 24-hour vertical motion of 40 mb is then given by taking the difference between A and B'. The results of these quasi-isentropic analyses for the 307 and 308 K surfaces appear in Table 2, where the method was applied to each day, firstly for 1 K and then for 2 K cooling rates per day.

SUMMARY OF RESULTS

The vertical motions obtained without allowance for diabatic cooling showed considerable variability in sign and magnitude (see Table 1), the largest value being a downward rate of 150 mb/day on the 306 K surface for day 28.

Table 1 Surface pressures at Daly Waters and isentropic pressures, D - at Daly Waters, A - upstream from Daly Waters, and B - downstream from Daly Waters

Day	Surface (mb)	306 K (mb)				307 K (mb)				308 K (mb)			
		D	A	B	A-B	D	A	B	A-B	D	A	B	A-B
1	-	-	805	830	-25	-	820	825	- 5	-	805	825	-20
2	995	770	770	780	-10	775	775	785	-10	755	755	770	-15
3	994	840	835	850	-15	810	815	820	- 5	800	805	790	+15
4	994	780	805	800	+ 5	790	790	805	-15	770	760	775	-15
5	991	780	780	785	- 5	790	790	800	-10	775	770	785	-15
6	992	790	780	810	-30	790	775	800	-25	790	785	785	0
7	992	800	785	795	-10	825	830	820	+10	800	785	895	-10
8	993	835	840	805	+35	870	830	815	+15	840	845	775	+70
9	992	830	845	815	+30	840	850	790	+60	815	820	770	+50
10	992	805	800	815	-15	815	810	830	-20	810	795	820	-25
11	991	840	840	840	0	850	835	840	- 5	840	845	825	+20
12	992	810	820	805	+15	820	805	825	-20	810	810	820	-10
13	991	800	770	830	-60	820	780	805	-25	800	790	785	+ 5
14	992	785	780	805	-25	810	790	800	-10	805	805	800	+ 5
15	990	750	770	755	+15	765	760	780	-20	750	750	770	-20
16	989	-	865	850	+15	750	745	760	-15	-	790	810	-20
17	989	765	775	775	0	775	775	780	- 5	765	780	775	+ 5
18	989	780	775	780	- 5	780	760	790	-30	785	770	775	- 5
19	990	755	760	765	- 5	750	740	750	-10	745	720	755	-35
20	991	775	780	780	0	780	770	765	+ 5	770	780	760	+20
21	991	795	795	805	-10	810	820	790	+30	790	795	785	+10
22	992	810	800	805	- 5	815	800	805	- 5	810	815	805	+10
23	992	790	800	785	+15	800	805	790	+15	790	790	785	+ 5
24	992	790	790	785	+ 5	800	800	790	+10	790	795	800	- 5
25	992	780	775	785	-10	780	770	790	-20	780	780	780	0
26	993	775	770	780	-10	775	765	785	-20	770	760	775	-15
27	994	740	730	760	-30	740	710	760	-50	735	730	735	- 5
28	994	700	655	805	-150	705	680	785	-105	-	725	770	-45
29	994	750	735	765	-30	780	735	755	-20	745	750	750	0
30	994	730	720	745	-25	780	750	780	-30	720	720	720	0

Table 2 Isentropic pressures upstream and downstream from Daly Waters with the primed values indicating allowance for diabatic cooling.

Day	306 K (mb) 2 K cooling			308 K (mb) 1 K cooling			307 K (mb) 1 K cooling		
	A	B'	A-B'	A	B'	A-B'	A	B'	A-B'
1	805	830	-25	805	825	-20	820	830	-10
2	755	780	-25	755	785	-30	775	780	- 5
3	805	850	-45	805	820	-15	815	850	-35
4	760	800	-40	760	805	-45	790	800	-10
5	770	785	-15	770	800	-30	790	785	+ 5
6	785	810	-25	785	800	-15	775	810	-35
7	785	795	-10	785	820	-35	830	795	+35
8	845	805	+40	845	815	+30	830	805	+25
9	820	815	+ 5	820	790	+30	850	815	+35
10	795	815	-20	795	830	-35	810	815	- 5
11	845	840	+ 5	845	840	+ 5	835	840	- 5
12	810	805	+ 5	810	825	-15	805	805	0
13	790	830	-40	790	805	-15	780	830	-50
14	805	805	0	805	800	+ 5	790	805	-15
15	750	755	- 5	750	780	-30	760	755	+ 5
16	790	850	-60	790	760	+30	745	850	-105
17	780	775	+ 5	780	780	0	775	775	0
18	770	780	-10	770	790	-20	760	780	-20
19	720	765	-45	720	750	-30	740	765	-25
20	780	780	0	780	765	+15	770	780	-10
21	795	805	-10	795	790	+ 5	820	805	+15
22	815	805	+10	815	805	+10	800	805	- 5
23	790	785	+ 5	790	790	0	805	785	+20
24	795	785	+10	795	790	+ 5	800	785	+15
25	780	785	- 5	780	790	-10	770	785	-15
26	760	780	-20	760	785	-25	765	780	-15
27	730	760	-30	730	760	-30	720	760	-40
28	725	805	-80	725	785	-60	680	805	-125
29	750	765	-15	750	755	- 5	735	765	-30
30	720	745	-25	720	780	-60	750	745	+ 5

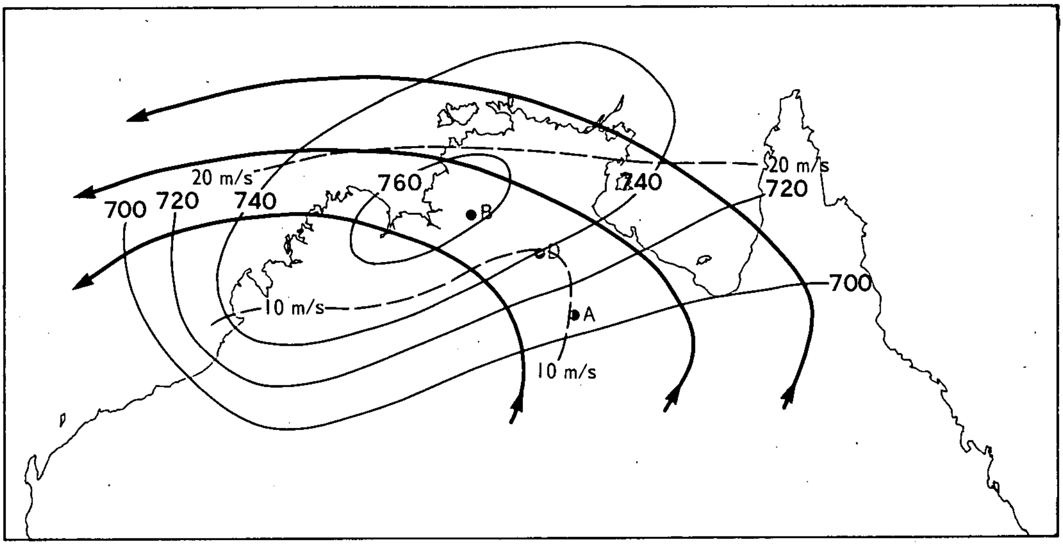

Fig. 3 θ = 307 K surface (day 27).

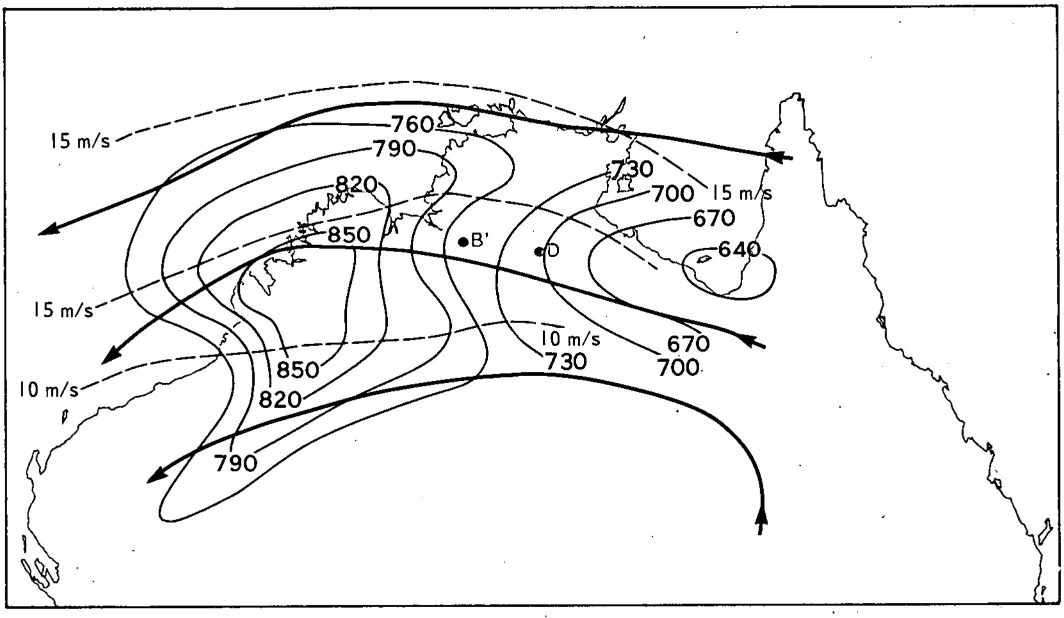

Fig. 4 θ = 306 K surface (day 27).

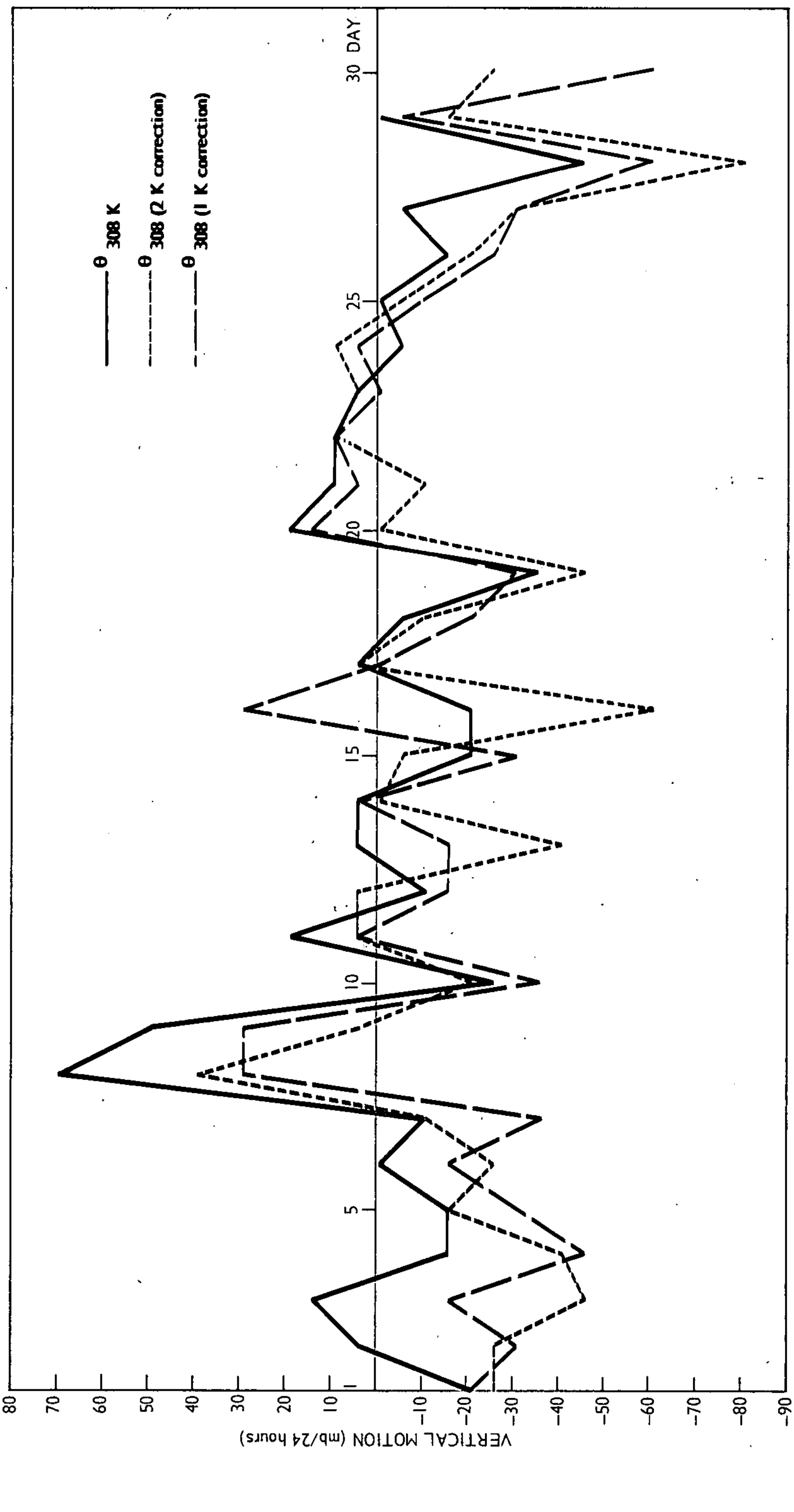

Fig. 5 Estimated vertical motions.

The magnitude of this was approximately twice the magnitude of the greatest upward motion of 70 mb/day, which occurred on the 308 K surface on day 8.

Application of a 2 K and 1 K cooling rate is demonstrated in Fig. 5, where vertical motions based on the 308 K surface are compared. The largest corrections apply to days 8, 16, and 28. The agreement over the thirty-day period appears to be reasonable, apart from day 16, where a change in sign of the vertical motion occurred between the 306 K and 308 K surfaces. As one would expect the effect of diabatic cooling was to decrease upward motion and increase downward motion. Days 8 and 28 again are good examples of this effect.

It should be remembered that this is a kinematic approach that is heavily dependent on the positioning of the isentropic pressure centres. As shown in Fig. 6 these centres are mobile and it is very difficult to locate the exact centre. Consequently a radical change in the sign of the vertical motion can occur in the vicinity of these centres, leading to great uncertainty in these areas.

The results show that on many days vertical motion correction estimates were smaller than the root mean square error inherent in the method, however on days of large vertical displacements the vertical motion corrections were larger than inherent errors and the method can be used justifiably.

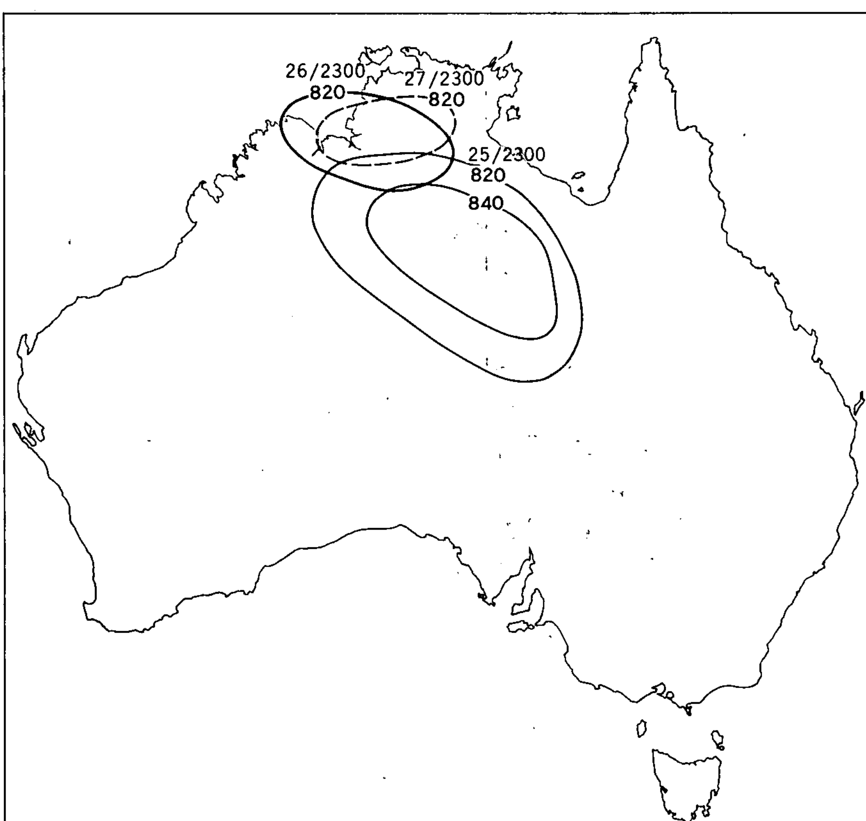

Fig. 6 Position of high centres on θ = 34°C for 3 consecutive days.

ACKNOWLEDGMENTS

The author thanks Dr R.R. Brook and Mr S.C. Allen for guidance and suggestions in the preparation of this paper and Mr R.S. Lourensz and Mr C.H. Giblin for assistance with computations.

REFERENCES

Cattle, H. and Weston, K.J. 1974. The determination of large scale vertical motion by a modified isentropic technique. *Met. Mag., Lond., 103*, 82.

Clarke, R.H., Dyer, A.J., Brook, R.R., Reid, D.G. and Troup, A.J. 1971. The Wangara experiment: boundary layer data. *Tech. Pap. 19*, CSIRO Div. Met. Phys., 362 pp.

Cox, S.J. 1969. Radiation models of midlatitude synoptic features. *Mon. Weath. Rev., 97*, 637.

Danielson, E.F. 1961. Trajectories, isobaric, isentropic and actual. *J. Met., 8*, 479.

Green, J.S.A., Ludlam, F.H. and McIlveen, J.F.R. 1966. Isentropic relative-flow analysis and the parcel theory. *Q. Jl R. met Soc., 92*, 201.

Myers, V.A. 1966. *Tech. Note, 44-HYDRO-1*. US Department of Commerce.

Namias, J. 1940. *Air Mass and Isentropic Analysis*. (Am. Met. Soc.: Milten, Mass.) 136.

Plate, E.J. 1971. *Aerodynamic Characteristics of Atmospheric Boundary Layers*. (USAF Division of Technical Information Extension: Oak Ridge, Tenn.) 121.

Rossby, C.G. 1932. Thermodynamics applied to air mass analysis. *Pap. phys. Oceanogr. Met., 1*,