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The derivation of 500 hPa height from automatic weather station surface observations in the Antarctic continental interior

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At the present time Amundsen-Scott (South Pole, elevation 284 geopotential decametres (gpdam)), and Vostok, 78.5°S, 106.9°E, 350 gpdam, are the only operational rawinsonde stations in the Antarctic continental interior. However, a larger number of automatic weather stations (AWS), providing surface pressure and temperature data, have been installed by Australia, France, Japan and the United States of America. From an analysis of radiosonde observations made during the International Geophysical Year (1957–58) at five US and USSR stations ranging in elevation from Byrd (153 gpdam) to Sovietskaya (367 gpdam), it is shown that 500 hPa heights can most probably be estimated with acceptable accuracy from these AWS surface observations, at sites of 2.5 km or higher elevation.

Introduction

We are concerned with the broad problem of surface weather behaviour in the Antarctic south of latitude 60°S, between 45°E and 160°E, which, for convenience, will be referred to as the Indian Ocean sector of East Antarctica (IOEA). A major objective is to develop an Australian capability of providing accurate forecasts of the expected cloud, surface wind, weather and visibility conditions on the IOEA coast to support the safe operation of intercontinental transport aircraft, and to be available about 15 hours before the expected time of arrival at an Antarctic terminal.

Neither the density nor the reporting frequency of the continental observing station network is good for our requirement, and communication channels between Antarctic stations are still rather unreliable. These difficulties, however, are set aside and the problem of analysing the charts from which the terminal forecasts must be made is examined.

By far the most commonly used chart for surface weather forecasting is that showing the MSL pressure (MSLP) distribution. With a good frontal analysis superimposed, it is the basic tool for the forecaster. However on the Antarctic continent, and particularly in East Antarctica, the nature of the atmospheric processes considerably reduces the utility of the conventional frontal approach; the surface wind behaviour is not well understood, the remote sensing of cloud cover presents problems, and moreover, the height of the ice mass precludes the use of the MSLP field. We agree with Schwerdtfeger (1984)... 'that sea-level isobars on the antarctic plateau do not have a clear physical meaning ...', and therefore a more suitable base or reference level needs to be selected. During the International Geophysical Year (IGY, 1957–58) the 700 hPa surface was frequently used as the base level over the continent, whilst Voskresenskii and Chukanin (1986) have discussed the results of the analyses of 600 hPa contour charts, a level which 'practically never touches the surface of the highest parts of the continent'.

We have been studying this weather behaviour problem for some time, based on the premise that over East Antarctica the 500 hPa contour field should replace the MSLP field as the principal reference level south of latitude 60°S. The height of this surface is generally about 5 km above MSL,

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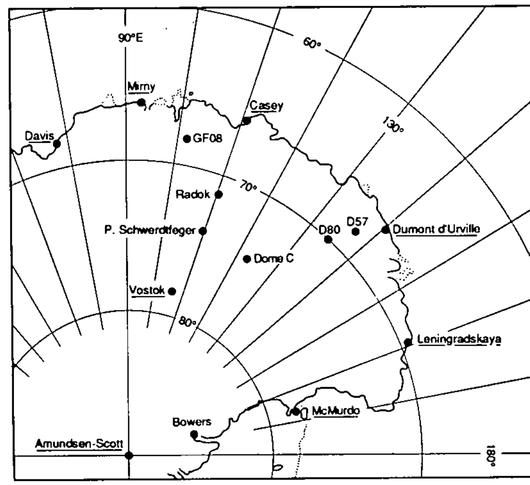
i.e. only about 1–2 km above the continental snow or ice surface, and much less above the strong surface temperature inversion in winter. It is therefore effectively a gradient wind level over a large area of the continental interior. Furthermore this pressure level is one for which observational data are always included in upper-air reports.

Charts and data kindly provided by the National Meteorological Centre (NMC) Melbourne have been used. Our practice has been to amend or revise the 500 hPa height (Z500) contour field, which (as given) shows contours at 120 m intervals, by including additional contours at 40 m intervals. These identify the significant field features more clearly. The salient features of the NMC analyses are retained, but all observations on the station time-section records, including the detailed surface pressure and wind behaviour, are used to identify the circulation systems. We reposition pressure centres, if necessary, to achieve the most logical historical continuity. Close attention is given to the likely slopes of the axes of pressure systems from 500 hPa to the surface to decide their likely MSL positions between 60°S and the continental coastline, but we seek to relate the observed surface weather behaviour to the development and movement across the area of pressure systems identified at the 500 hPa level.

The surface wind behaviour at Dumont d'Urville is particularly interesting. This station is located (66.7°S, 140.0°E) near the section of the coast where very persistent high-speed surface winds occur (Loewe 1974). We wish to establish the cause of these, and the role played by the synoptic-scale pressure gradient force. There are only two upper-air observing stations in the continental interior, Amundsen-Scott (South Pole) and Vostok (78.5°S, 106.9°E), but several automatic weather stations (AWS) have been installed on the continent between 90°E and 180°, at the locations shown in Fig. 1. These provide useful information in monitoring surface pressure trends, and in the high interior should reflect Z500 changes. However the most useful and effective approach by far, particularly with the Dumont d'Urville problem in mind, would be the derivation of Z500 values from the AWS observations, and their incorporation in the contour field analyses.

Fig. 1 **Sites above 2 km elevation where AWS have been installed in East Antarctica. GF08, Radok, P. Schwerdtfeger, Dome C, D80, D57, Amundsen-Scott (Cleanair), Bowers. (Wintering bases (current 1989) are also shown underlined.)**



pressure field. Both station surface-level pressure and temperature values are strongly influenced by elevation.

Derivation of the 500 hPa height requires the observed values of station-level pressure and temperature, and (estimated) vertical temperature and moisture profiles through the atmospheric layer between the surface and the 500 hPa level. This layer is about 1.5 km deep over a quite extensive area of the continent. It increases in depth towards the coast, and the strong surface temperature inversion introduces a major complication, particularly over the continental interior in winter (Phillpot and Zillman 1970).

The representativeness of mean monthly surface temperatures for deeper atmospheric layers has previously been addressed (Phillpot 1968, p.34). We were concerned that the strong surface temperature inversion might affect the representative nature of the mean surface temperature. However, using data from five Antarctic station sites between the coast and Amundsen-Scott, it was found that lower surface air temperature was associated with lower temperature through a significant depth of the Antarctic troposphere, even at the inland stations. It was concluded that surface temperature could be accepted as representative of a deeper air layer, despite the presence of the strong temperature inversion.

Schwerdtfeger (1984, p.36) also noted that ... 'many thousands of radiosoundings carried out ... in the interior of the continent ... leave no doubt that normally there is a rather thick layer between, say, 500 and 1500 m (above surface) in which the temperature changes but little with height.'

The problem

Automatic weather stations provide observations of surface wind direction and speed; station-level pressure; and air temperature at one or more levels, but all relatively close to the snow surface.

The surface wind observations are probably of limited use for our purposes. Whilst experience may well show that more can be learned from them than is presently believed, no inferences can be drawn on their likely relationship to a surface

The earlier conclusion applied to mean conditions, but it is likely that a layer-mean air temperature at a particular time can be estimated from the surface air temperature with a tolerable degree of accuracy for a layer 1.5 km deep. This accuracy will decrease as the atmospheric layer depth increases. A 'tolerable' degree of accuracy indicates reasonable confidence that the estimated 500 hPa height is within four decametres, i.e. the preferred contour interval for field representation.

The problem is therefore to verify this view, and also to determine the probable maximum layer depth for which an acceptable estimate can be made.

Procedure

During the IGY, the USSR maintained three stations in the interior of East Antarctica through 1958: Pionerskaya (69.7°S, 95.5°E; elevation 2700 m); Vostok (78.5°S, 106.9°E, 3420 m), and Sovietskaya (78.4°S, 87.6°E, 3570 m). The upper-air observations for these stations were published in detail by Dolgin (1962). The USA operated two stations, Byrd (80.0°S, 120.0°W, 1515 m) in West Antarctica and Amundsen-Scott (South Pole, 2808 m), the upper-air observations for which are available in the WMO microcard series for the IGY period (July 1957 to December 1958). The number of flights, their frequency, and the observational periods are given in Table 1.

With the conventional technique for computing the pressure-height curve for a radiosonde flight in mind, these observations have been used to determine:

(a) the pressure difference (Δp) between 500 hPa and the observed station-level pressure for each ascent;
(b) the thickness of this stratum (ΔZ_1) for a mean virtual temperature (MVT) of 0°C for each ascent (the Smithsonian tables were used for this);
(c) the radiosonde-calculated thickness of the layer between 500 hPa and the surface level (ΔZ_2). This is an accurate measure of the true MVT for the layer on each ascent;
(d) the difference $\Delta Z_1 - \Delta Z_2$, which represents the thickness correction ΔZ_T required by the departure of the layer true MVT from 0°C;
(e) linear regression equations relating the observed surface air temperature T°C (1°C class intervals), and the values of ΔZ_T obtained in (d); and finally
(f) the standard deviation of the departure of the layer thickness from the mean value, for each 1°C surface temperature class interval.

As an example, Fig. 2 illustrates the regression equation for Amundsen-Scott where the total number of flights available was 918. The line slope is 0.27 gpdam/°C, the y-axis intercept −21.60 gpdam, and the standard deviation 2.31 gpdam. Many of the plotted points represent more than one observation of course, but the range of thickness layer corrections for any surface air temperature value is evident.

The results of analyses for each station are shown in Table 1.

The station elevations shown in Table 1 are in gpdam. However the small correction required to adjust geometric to geopotential height can be ignored because of elevation uncertainty in the continental interior, and they can be regarded as decametres above MSL. Furthermore they are the most recent values, but inaccuracies in the earlier determinations can be disregarded because thickness values, for a given pressure interval, are functions of MVT only.

Interesting points in Table 1 are that, excluding

Table 1. The station elevation (gpdam); the number of flights available and their frequency; the characteristics (m,c) of the linear regression $\Delta Z_T = mT + c$ (for explanation see text); and the standard deviation (sd) of each observational sample at Byrd, Pionerskaya, Amundsen-Scott, Vostok and Sovietskaya.

Station	*Elevat. (gpdam)*	*No. of flights*	*Freq.**	*m line slope (gpdam/°C)*	*c y axis intercept (gpdam)*	*sd (gpdam)*
Byrd	153	957	2	0.51	−25.84	4.29
Pionerskaya	276	130	1	0.36	−17.60	2.12
Amundsen-Scott	284	918	2	0.27	−21.60	2.31
Vostok	350	343	1–2	0.24	−14.87	1.71
Sovietskaya	367	277	1	0.19	−14.71	1.76

*General frequency — flights per day.
Observational periods — Byrd, Amundsen-Scott: 1 July 1957 to 31 December 1958.
Pionerskaya: 13 March to 22 April 1958 and 14 October 1958 to 10 January 1959.
Vostok: 1958, broken record in April and July.
Sovietskaya: 16 March to 31 December 1958, broken record in September.

Fig. 2 Distribution, over the observed range of surface air temperature, of the corrections (gpdam) required to the thickness of the atmospheric layer between 500 hPa and the surface by the departure of the layer-observed MVT from 0°C, at Amundsen-Scott during the (IGY) period July 1957–December 1958. The derived linear relationship, and the limits representing thickness departures of ± 4 gpdam from the mean, are also shown.

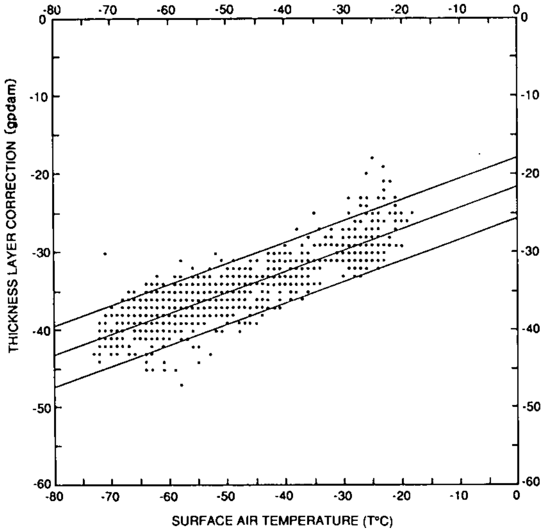
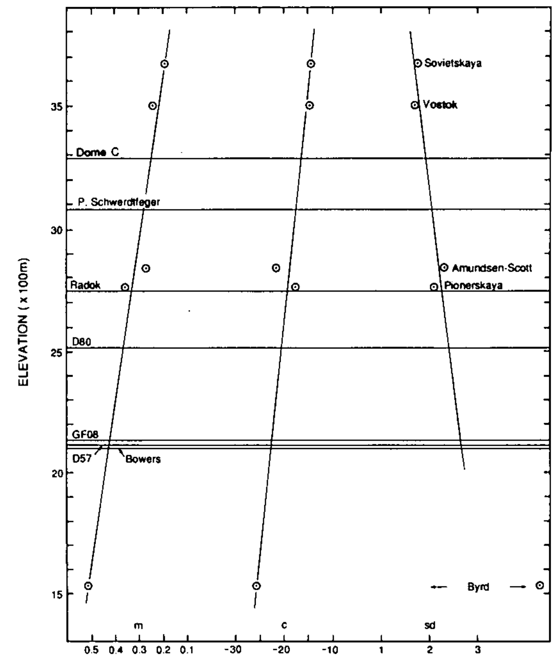


Fig. 3 The variation of regression line slope (m), y-axis intercept (c), and the standard deviation (sd), between 1500 and 3800 m elevation over the Antarctic continent based on regression relationships derived from IGY observational data for Sovietskaya, Vostok, Amundsen-Scott, Pionerskaya and Byrd (see text for explanation).



Byrd, the line slope, m, is relatively small, a 10°C change in surface temperature at Amundsen-Scott, Vostok or Sovietskaya leads to a change in thickness correction (ΔZ_T) of only 2.7 to 1.9 dam, which is most encouraging. The difference between Pionerskaya and Amundsen-Scott, both near the same height, may arise from differences in station location — Pionerskaya in the colder area of East Antarctica, Amundsen-Scott more typical of the cloudier West Antarctica. However differences between the required thickness corrections, as derived from the regression equations over a surface temperature range from −15° to −50°C at these two stations, seldom exceeded two gpdam, arising in part because the larger slope value, m, at Pionerskaya is compensated by a smaller c value.

Turning to values of the standard deviation, sd, accuracy limits of ± 4 gpdam in the estimated 500 hPa height require that the sd should not exceed 2 gpdam on about 94 per cent of occasions, assuming a normal distribution. Amundsen-Scott and Pionerskaya are both slightly above the desired limit, and if the value at Byrd is representative, the sd value clearly increases quite rapidly and probably exceeds 2.5 gpdam below about 2400 m. It is therefore doubtful whether this technique can be applied to station sites much below 2.4 km elevation, and certainly not down to that of Byrd (≃1.5 km).

Application to the present AWS network

The present AWS network includes stations above the 2 km level. To derive regression equations for them we have plotted against height the m, c and sd values for the five stations in Table 1, determined lines of best fit by eye, and taken the m and c values for each (known) AWS elevation (Fig. 3). Despite our earlier reservation about Byrd, it is interesting that the m and c values there appear quite reasonable, but it is the likely error in an estimated thickness correction which makes the technique unacceptable at this low elevation.

Table 2. AWS sites with elevation, geographical location and regression relationships (as explained in the text).

	Elevation (gpdam)	*Lat. (°S)*	*Long. (°E)*	*Regression relationship*
GF08	213	68.5	102.2	0.42T−22.50
Radok	275	71.6	111.3	0.33T−19.30
P. Schwerdtfeger	308	74.1	109.8	0.28T−17.50
D57	211	68.2	137.5	0.43T−22.50
D80	251	70.0	134.7	0.36T−20.50
Dome C	329	74.5	123.0	0.25T−16.50
Bowers	210	85.2	163.4	0.43T−22.60
South Pole (3 Stations)	284	90°S	—	0.27T−21.60
Vostok	350	78.5	106.9	0.24T−14.87

Table 2 shows the AWS sites, their elevation and location, and the regression relationships.

GF08, D57 and Bowers have been included in Table 2 although we recognise that the accuracy of the estimated 500 hPa height decreases below the 2.4 km level. The South Pole has also been included because three AWS have been installed in close proximity to the upper-air sounding station, and can provide useful supplementary information. Similarly at Vostok, we can satisfactorily estimate the 500 hPa height if reports of station-level pressure and surface temperature are received.

500 hPa heights can be estimated from these AWS (or station) surface pressure and temperature observations and the site elevation by a procedure similar to that used earlier in establishing the station regression equations, namely by:

- finding the depth of the atmospheric layer (in gpdam) between 500 hPa and the observed station-level pressure for MVT 0°C;
- using the appropriate regression equation to determine the correction (ΔZ_T dam) to this thickness arising from the departure of the layer MVT from 0°C; and
- adding the corrected layer thickness to the AWS elevation.

Reliability assessments

The reliability of 500 hPa height estimates was assessed from surface data at these stations by tests of three types: at Amundsen-Scott, from which both radiosonde and independent near-simultaneous AWS observations are available; at Vostok, from which rawinsonde ascents are available; and at AWS sites, where no radiosonde ascents are available. Data were used for the period December 1986 to February 1987 from the complete network of Australian and French-US AWS observations, and for August 1989 only the Australian AWS data were available at the time of writing.

Consider first Amundsen-Scott. In the 90-day period December 1986 to February 1987, observations from 46 rawinsonde flights were received. Surface observations from the nearby Cleanair AWS (Sievers et al. 1988) enabled 500 hPa heights to be estimated for times corresponding to the radiosonde flights. The numbers of cases of specified difference between the radiosonde-determined and estimated heights are given in Table 3 at line (a). These show differences of 1 dam or less on 23 flights (i.e. 50 per cent), and differences

Table 3. The number of cases of specified difference (dam) between 500 hPa radiosonde-determined (RD) heights and values estimated (E) from surface pressure and temperature data only. December 1986–February 1987 at Amundsen-Scott and Vostok, and August 1989 at Vostok.

		No. of cases of specified difference RD-E (dam)										
	Total obs	*>−4*	*−4*	*−3*	*−2*	*−1*	*0*	*+1*	*+2*	*+3*	*+4*	*>+4*
(a)	46	1	.	.	1	8	7	8	6	6	6	3
(b)	88	.	1	9	6	25	22	11	8	5	1	.
(c)	25	.	.	1	.	4	5	5	3	6	1	.

(a) Amundsen-Scott, December 1986–February 1987; (b) Vostok, December 1986–February 1987; and (c) Vostok, August 1989.

greater than 4 dam on only four flights (≃9 per cent). In August 1989, 18 radiosonde observations giving 500 hPa heights were received, but no, or incomplete, surface data were available with 16 of them. On the two flights where surface data were available, the 500 hPa height differences were −1 and +2 dam respectively.

At Vostok, through the 90-day period, observations from 88 radiosonde flights enabled differences to be determined between the observed 500 hPa height and values estimated from the surface data included on the flight message. The results, Table 3 line (b), show that differences of 1 dam or less were found on 58 (66 per cent) of occasions, but none was greater than 4 dam. In August 1989 observations from 25 radiosonde messages at 0000 UTC showed differences (Table 3, line (c)) which fall within the 4 dam limit, the order of accuracy we wish to achieve.

It is important to note here that only about 50 per cent of the daily rawinsonde flights were received from Amundsen-Scott in the December 1986 to February 1987 period, whereas the satellite-relayed AWS observations were lost on only one day.

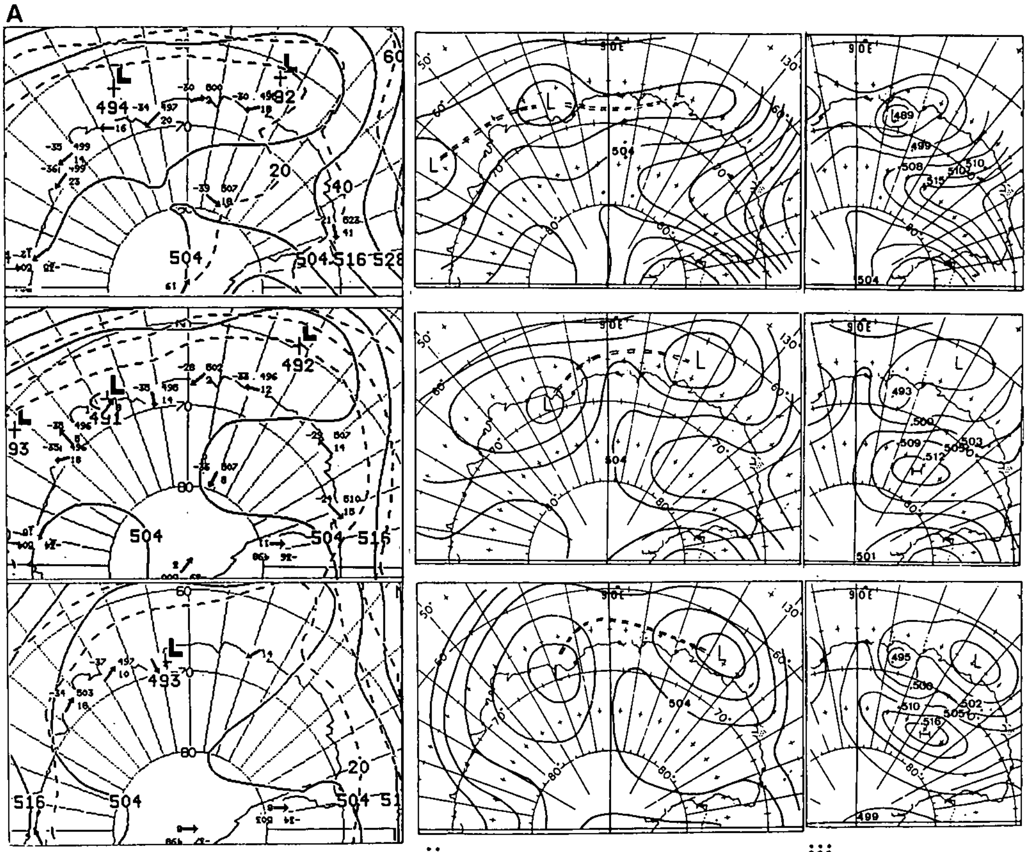
We turn now to the third type of assessment — namely that of determining the likely reliability of 500 hPa height estimates from AWS sites with no radiosonde flight support.

The sites and assessments are:

(a) Radok — the favourable comparison made earlier between Amundsen-Scott and Pionerskaya, and the small elevation difference between the three stations, support the view that the proposed regression relationship is

Fig. 4 (i) The Melbourne NMC 00UTC 500 hPa contour/isotach analyses over East Antarctica and adjacent waters.
(ii) The contour field, revised or amended, over the continent.
(iii) The contour field, further revised by incorporating 500 hPa heights estimated from the AWS observations shown.
(a) For 3–4–5 December, and (b) 23–24 December, 1986.

A



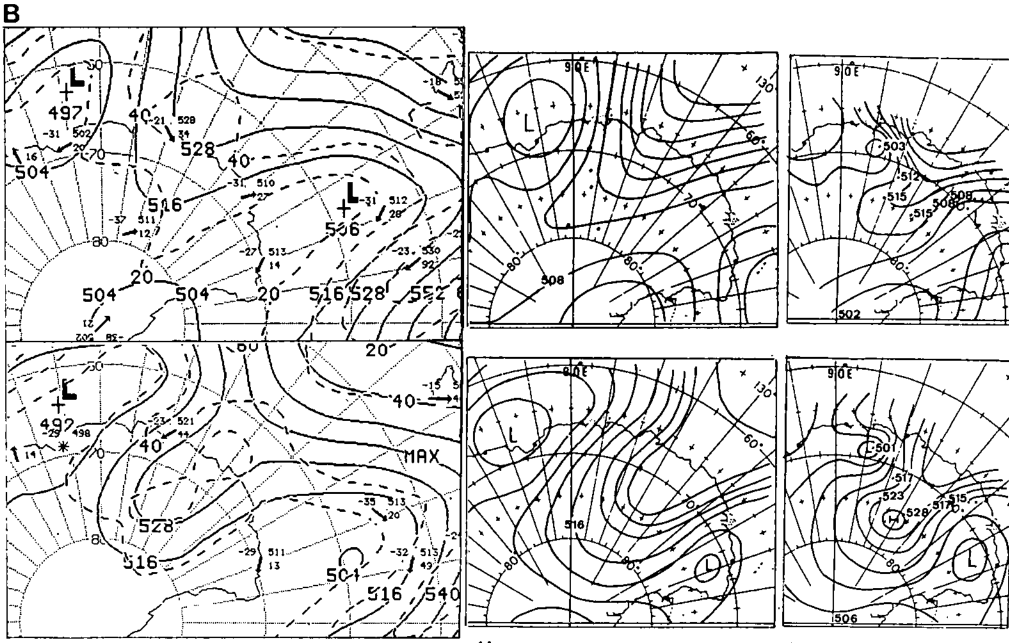
3 Dec.

4 Dec.

5 Dec.

i ii iii

B



23 Dec.

24 Dec.

i ii iii

unlikely to result in significant height-estimate errors there;

(b) Dome C, P. Schwerdtfeger, D80 — the relationships shown in Fig. 3 suggest that the regression equations derived for these stations should provide useful 500 hPa height estimates;

(c) GF08, D57, Bowers — all three stations are near the same elevation (2.1 km). More serious errors might be expected because of the greater depth of the atmospheric layer ($\simeq$3 km) for which the MVT is being estimated.

Having no radiosonde data at these sites we examine two periods 3 to 5 and 23 to 24 December 1986. In Fig. 4 we show for each period: (i) the Melbourne NMC 0000 UTC 500 hPa contour/isotach analyses for East Antarctica; (ii) the amended 500 hPa contour fields, obtained as described earlier by considering data included on the station time-sections etc.; and (iii) a further revision of the 500 hPa contour fields using heights estimated from AWS surface observations GF08, Radok, P. Schwerdtfeger, Dome C, D80, D57 and the South Pole station, Cleanair.

The surface pressure observations for P. Schwerdtfeger were rather 'noisy', but the estimated heights, including D57 but not GF08 give consistent contour field patterns. They certainly conform with the quite significantly different orientation of the 500 hPa contour ridge shown on each of the two examples, and there seem to be reasonable grounds for accepting them as reliable.

We appear able to derive additional interesting information from these two examples. In the first a 'strong wind event' at Dumont d'Urville was identified, i.e. a condition when the 850 hPa wind speed exceeded 20 m/s. In the second period we again observed a strong low-tropospheric wind regime at d'Urville, but one which conformed more with a class we have defined as an 'enhanced katabatic surface wind', i.e. one where the maximum wind speed occurs at, or just above the surface and, although decreasing with height, exceeds 5 m/s at 850 hPa (Phillpot 1989).

During each of these periods the AWS between Dome C and Dumont d'Urville showed the surface wind speeds were relatively high. More particularly, the surface wind directions showed a marked easterly component in the first period, but a southerly component in the second, which is consistent with the 500 hPa contour field. We might conclude that these surface wind direction observations along the ice ridge, where katabatic effects are likely to be minimal, could be representative of the gradient-level wind regime.

The GF08 estimated heights require comment. It would be easy to dismiss them as too low, arising from errors in the estimation procedure to which we have drawn attention, or perhaps in station elevation, but we believe further investigation is required here. Not only are the 500 hPa heights at D57, at very near the same elevation as GF08, consistent with the broad field (no observations are available from Bowers), but in a separate test for August 1989 we found that the station level pressure at GF08 was so frequently lower than the pressure at the equivalent height on near-simultaneous radiosonde flights at Casey, that another problem was being identified. This, however, is beyond the scope of this paper.

Concluding comments

We have emphasised the need to improve our understanding of surface weather behaviour in the area we call the Indian Ocean sector of East Antarctica. This understanding rests on the quality of the synoptic charts used to study the relationship between surface weather conditions and the development/movement of pressure systems over the area.

The 500 hPa contour field is seen as the best one to use to establish this relationship, and we seek to improve the quality of the contour analyses by estimating 500 hPa heights from values of surface pressure and temperature at station sites. The technique utilises a high correlation between the MVT of the atmospheric layer between station elevation and 500 hPa, and the station surface air temperature, although this correlation decreases with increasing layer depth. Our results appear encouraging for application to sites above 2.5 km elevation, but not at lower levels. Furthermore, the estimated heights appear much too low at one AWS (GF08, 68.5°S, 102.2°E, 2.1 km) and the reason for this is unclear.

We recognise the likelihood of observational and instrumental error. Whilst the accuracy of the surface temperature observations is not particularly critical because of the relatively low values of regression line slope ($\simeq$0.3 gpdam/°C), a surface pressure error of 1 hPa will give rise to a height error of 1 to 1.5 decametres. Some degree of radiosonde instrumental error is likely but we cannot assess this. Over many years of involvement in Antarctic upper-air analysis, we have not been conscious of significant and regular differences between observations derived from different types of radiosonde equipment used by Antarctic nations, although the sparse observing network may of course conceal this.

Many aspects of this problem have not been explored. For example, we have not attempted to subdivide our station data-sets on a seasonal basis. We preferred not to do this partly because such a subdivision raises problems in the 'intermediate' seasons. The similarity between the results for Pionerskaya and Amundsen-Scott, despite the absence of observations at Pionerskaya through the winter, suggests this is not a major deficiency in the method.

A data subdivision based on a 500 hPa circulation pattern type might prove interesting. Satellite-derived 500 hPa temperature fields over the Antarctic continent, if sufficiently accurate, might also lead to improved estimates of the layer MVT and perhaps permit the method to be extended to lower elevation station sites.

The two examples we have given illustrate that much might be learned from studies of the AWS data, and we feel confident that application and testing will lead to further significant improvements in both the contour analyses and our understanding of the continental weather behaviour.

Acknowledgments

I am indebted to my colleagues in the Department of Meteorology and to Professor U. Radok of the Cooperative Institute for Research in Environmental Sciences (CIRES), Boulder, Colorado, for their criticisms, constructive comments, and continuing interest in this ongoing study of Antarctic weather behaviour. I particularly appreciate the help given by Ms E. Mavrakis, who, using a program prepared by Dr D. Jenssen, verified the regression equations on which this technique rests. Discussions with Dr I. Allison and Mr N.W. Young on Antarctic station elevation determination, and suggestions offered by two anonymous reviewers, were most useful.

References

Dolgin, I.M. 1962. Soviet Antarctic Expeditions: Third continental expedition 1958–9. *Meteorological observations II*, Leningrad, 477pp.

Loewe, F. 1974. Considerations concerning the winds of Adelie Land. *Zeitschrift fur Gletscherkunde und Glazialgeologie, 10*, 189–97.

Phillpot, H.R. 1968. A study of the synoptic climatology of the Antarctic. *IAMRC Tech. Rep., 12*, Bur. Met., Australia, 139pp.

Phillpot, H.R. 1989. On surface weather behaviour on the Australian Antarctic Territory coastline — 1: An observational overview. *Conf. and Workshop on Antarctic Weather and Climate, Adelaide, July 1989. Extended abstracts*, Bur. Met., Australia, 28–38.

Phillpot, H.R. and Zillman, J.W. 1970. The surface temperature inversion over the Antarctic continent. *J. geophys. Res., 75*, 4161–9.

Schwerdtfeger, W. 1984. *Weather and climate of the Antarctic.* Elsevier, Amsterdam, 261pp.

Sievers, M.F., Weidner, G.A. and Stearns, C.R. 1988. *Antarctic automatic weather station data for the calendar year 1987.* Department of Meteorology, University of Wisconsin, USA, 299pp.

Voskresenskii, A.I. and Chukanin, K.I. 1986. Main features of atmospheric circulation over Antarctica. In *Climate of Antarctica*, I.M. Dolgin (ed.), Russian Translations Series 41, A.A. Balkema/Rotterdam, 178–85.