Aust. Met. Mag. 53 (2004) 103-110

Fictitious pressure gradients arising from reductions to sea level over central Australia

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(Manuscript received December 2002; revised December 2003)

When two nearby stations are at similar heights above sea level, a fictitious increment to the gradient of sea-level pressure may be introduced into the analysis by the different below-ground column-mean virtual temperatures used for reduction to sea level at each station. When the reduction method utilises a monthly climatological mean surface (screen) temperature and a standard lapse rate at each station, as the Australian method does, the fictitious increment is almost constant during a calendar month for a given pair of stations, and can be calculated in advance. Knowledge of these increments may be helpful both for analysis and for quality monitoring of sea level pressures.

Using two years of observations over central Australia (20°-27°S, 128°-137°E), it is shown that the largest systematic fictitious increments to the pressure differences between station pairs are between 0.7 and 0.9 hPa in most months. The geostrophic wind equivalent of these largest increments is of order 5 m s^{-1}. The increments usually make the pressure gradients too strong, but may produce gradient reversals on some individual days. There is also some correspondence between the spatial pattern of the fictitious increments, and the stations whose sea level pressures appear consistently higher or lower than expected from neighbours using cross-validation.

Introduction

Manual analysts have always been aware of the difficulty of analysing the sea level pressure field over high terrain, due to uncertainties from pressure reduction to sea level. When these uncertainties are random, there may be little alternative to simply treating the observations over high terrain as less reliable, and applying judicious smoothing. However, to the extent that it is possible to specify in advance, and to account for, any systematic effect arising from pressure reduction uncertainties, such observations may be used more effectively. This paper is directed towards the latter objective.

Unfortunately, as discussed later, such systematic effects are only significant over fairly limited geographical areas, namely where the topography is plateau-like rather than mountainous. Moreover, such systematic effects as do exist arise because of the particular pressure reduction method at Australian stations, which is different from that used in many other countries. But within these limitations, the results in later sections seem useful, and the underlying theory does not appear to have been previously noted.

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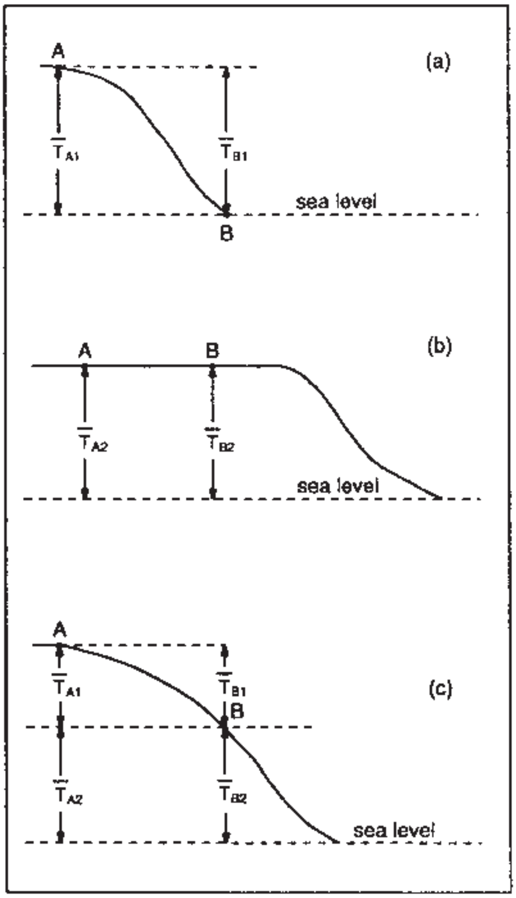
Over land areas above sea level, the sea-level pressure is by definition a hypothetical quantity. However, for a sea-level pressure analysis over the land to be most useful, its horizontal gradients should be well-related to the corresponding gradients in the real atmosphere at the level of the topography. Otherwise expressed, the procedure for reduction to sea level should not introduce excessive fictitious pressure gradients.

As discussed by Gibbs (1952) and many subsequent authors, there are two distinct sources of fictitious pressure gradients that can arise from reductions of pressures from station level to sea level. The first source is the difference between the mean virtual temperature of the fictitious air column below an elevated station, and the corresponding mean virtual temperature in the real atmosphere above a neighbouring station at sea level (Fig. 1(a)). The second source is the difference in mean virtual temperature between the two fictitious air columns below elevated stations at the same heights above sea level (Fig. 1(b)). The general case (Fig. 1(c)) can be regarded as a superposition of Figs 1(a) and 1(b). The first source is likely to dominate where most pairs of nearby points are like Fig. 1(a) (mountainous areas), while the second source will become more important where most pairs are like Fig. 1(b) (plateau-like areas). This paper focuses on the second source, and considers a study area (Fig. 2) centred upon Alice Springs in central Australia. The coverage of pressure reports over this area improved substantially during the 1990s, enabling a more meaningful study than would have been possible earlier.

Fig. 1 **Schematic representation of the sources of fictitious gradients discussed in the text. Symbols $\overline{T}_{A1}$ etc. denote mean virtual temperatures of the layers indicated by arrows. From Seaman (1997).**



Theory

The pressure reduction method used by the Australian Bureau of Meteorology since 1972, described by Colquhoun (1965, method (iii) therein), is based upon a fictitious below ground temperature sounding that uses a monthly mean surface (screen) temperature and a standard lapse rate. Specifically,

$$p_o = p \exp(0.034141\, H/T_{MV})$$

where $T_{MV} = T_M + 0.5aH + e_m(0.1070 + 0.0002508H)$

Here, p_o and p are the sea level and station pressures, H is the barometer height above sea level (m), T_{MV} is the mean virtual temperature (K) of the fictitious air column between station level and sea level, T_M is the monthly mean surface temperature (K), a is a standard lapse rate (0.0065 K/m), and e_m is the monthly mean vapour pressure (hPa). It follows that the factor

$$K = \exp(0.034141\, H/T_{MV}) \qquad ...1$$

is constant throughout a calendar month at a particular station, and a resultant discontinuity in pressure reduction occurs at the end of each month. The factors k, for each month at all stations, are known as the "k1 coefficients" in Australian operational terminology. They are pre-computed and used either directly at remote automatic weather stations, or indirectly in the form of lookup tables of pressure corrections by the weather observer.

In the case of Fig. 1(b), the fictitious increment of interest is the increment to the gradient of sea-level pressure that is an artifact of the below-ground reduction to sea level in the case of two elevated stations A and B, with the same station pressure, at the same height above sea level. Otherwise expressed, it is the gradient of sea-level pressure that would be observed if the gradient of station pressure in Fig. 1(b) was zero. So, at a particular observation time, the fictitious increment d is given by

$$d = p(k_A - k_B) \qquad \text{...2}$$

where p is the station pressure at A and B, and k_A and k_B are the $k1$ coefficients at A and B. For a calendar month of observations, the monthly mean of d is given by

$$\overline{d} = \overline{p}(k_A - k_B)$$

and the standard deviation of d by

$$\sigma_d = \sigma_p(k_A - k_B)$$

Typically, p is of order 1000 and σ_p of order 5, so that σ_d/d is of order 0.005. Therefore, to a good approximation d may be regarded as constant throughout a calendar month, and equal to $\overline{p}(k_A - k_B)$ where $\overline{p}$ is the monthly mean station pressure at the level of both A and B.

The discussion in the preceding paragraph related to the idealised case in Fig. 1(b). In a real station network, Fig. 1(b) never occurs exactly, because all station heights are at least slightly different. In the real world case (Fig. 1(c)), the corresponding fictitious increment of interest is that attributable to the below ground mean virtual temperatures $\overline{T}_{A2}$ and $\overline{T}_{B2}$ in Fig. 1(c). The corresponding k_A and k_B needed to calculate d from Eqn 2 may be obtained by substituting $\overline{T}_{A2}$ and $\overline{T}_{B2}$ in Eqn 1.

The fictitious increments d, corresponding to the lower layer of Fig. 1(c) for each month, can be calculated in advance, in the way just described, at the start of the month for all station pairs. This contrasts with the situation in Fig. 1(a) and the upper layer of Fig. 1(c), where the corresponding fictitious increments will vary from day to day with the synoptic situation. The advance knowledge of d, in the case of the lower layer of Fig. 1(c), may be useful both for analysis and for quality monitoring of observations, as will be discussed later.

Data and methods

Details of the pressure observing sites within the study area are shown in Fig. 2 and Table 1. During the two-year study period from October 2000 to September 2002, the number of stations regularly reporting within each month ranged from 9 to 15. The heights of the stations above sea level ranged from 329 m to 703 m. For the majority of possible station pairs, the vertical separation of the stations was much less than the height above sea level of the lower member. In other words, most pairs were considerably closer to Fig. 1(b) than to Fig. 1(a).

In each of the months, the fictitious increment d, defined in the previous section and almost constant for a particular pair, was computed for all station pairs. For the same pairs the statistics of the observed paired differences of sea-level pressure at 0000 UTC daily were calculated from SYNOP reports and compared with the fictitious increments. The spatial patterns of fictitious increments were analysed in order to detect any systematic spatial variations. The spatial patterns of fictitious increments were finally compared with the so-called ‘apparent biases’ at station locations, which are a byproduct of routine quality-control monitoring.

Results and discussion

The results in each month are sufficiently similar that it is necessary to discuss only one month (August 2001) in detail; significant seasonal variations will be mentioned only briefly.

Table 2 (column 3) shows the largest 25 values of d for station pairs during August 2001, sorted by absolute value. The largest absolute value is 0.82 hPa, and there are 25 absolute values over 0.40. Such magnitudes of fictitious increments are clearly of practical significance; field barometers are replaced if they differ consistently from a transfer standard barometer by more than 0.3 hPa. It is emphasised that the increments occur at every observation time during the month. The fictitious increments in most months are similar to those in Table 2, although there tend to be fewer large values in midsummer. The values of d in the third column correspond to fictitious geostrophic wind increments, shown in the fifth column of Table 2, which range characteristically up to 5 m s^{-1}.

The effect of the fictitious increments on daily sea-level pressure gradients between a particular pair of stations is shown in Fig. 3. The time series labelled ‘best estimate’ contains values of the observed difference minus the fictitious increment, and is a better estimate of the true gradient than is the observed difference. The fictitious increment of 0.77 hPa, which is present on every day, is in this case of a similar order to the best estimate of the true gradient. On several days, accounting for the fictitious increment produces a reversal in sign from that of the observed difference, but on most days the signs are the same. Similar reversals of gradient after accounting for pressure reduction effects have been noted by Hopwood (1978) over Western Australia.

Fig. 2 The central Australian study area (20°-27°S, 128°-137°E), with pressure observing stations (Table 1) shown. Tick marks are at latitudes 20 and 25, and longitudes 130 and 135.

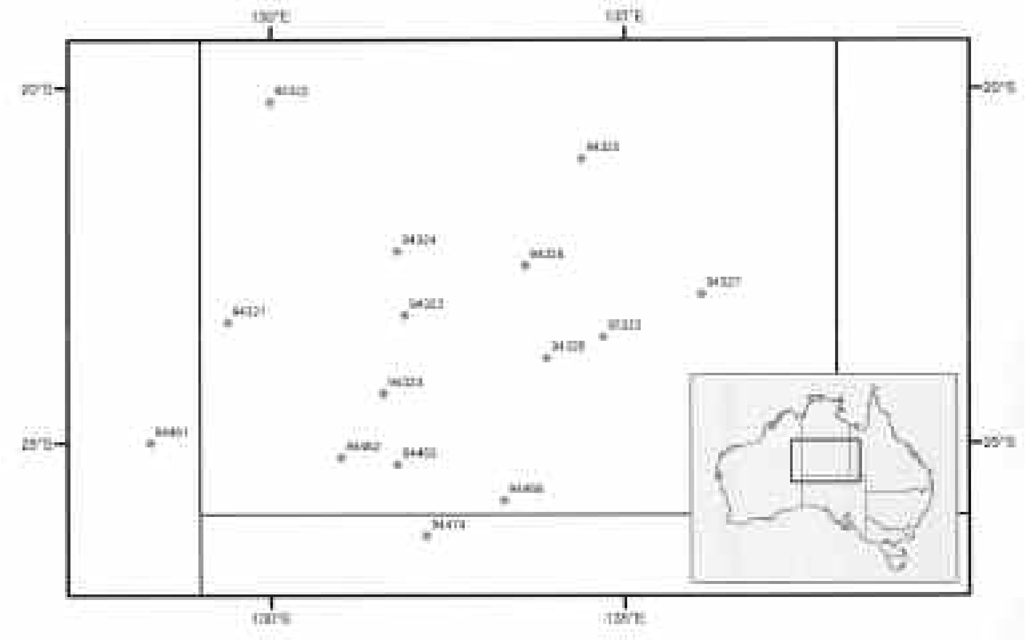


Table 1. Stations in the study area.

WMO Identifier	Station	Lat.(S)	Long.(E)	Barometer height (m)
94321	Wulungurru	23.3	129.4	455
94322	Papunyah	23.2	131.9	609
94323	Watarrka	24.3	131.6	612
94324	Yuendumu	22.3	131.8	668
94325	Ali Curung	21.0	134.4	376
94326	Alice Springs Aero	23.8	133.9	547
94327	Jervois	22.9	136.1	329
94328	Territory Grape Farm	22.5	133.6	567
94461	Giles Met Office	25.0	128.3	509
94462	Yulara Aero	25.2	131.0	492
94463	Curtin Springs	25.3	131.8	491
94466	Kulgera	25.8	133.3	510
94474	Pukatja	26.3	132.2	703
95322	Rabbit Flat	20.2	130.0	339
95323	Arltunga	23.5	134.7	664

Column 4 of Table 2 shows the monthly mean observed paired difference of sea-level pressure ($\overline{\Delta p}$) corresponding to the 25 station pairs. The observed paired differences of course include the effects of the fictitious increments. There is strong correlation between d and ($\overline{\Delta p}$), as is evident from the corresponding scatter-plot of all station pairs (Fig. 4). The fictitious increments d are such that they tend to rein-

Table 2. **The 25 station pairs (A,B) with the largest fictitious increments *d* (hPa) during August 2001. The column $\overline{\Delta p}$ (hPa) contains the observed monthly mean difference at 0000 UTC, and the column *egeos* is the geostrophic wind (m/s) corresponding to *d*.**

A	*B*	*d(A-B)*	$\overline{\Delta p}$	*egeos*
94324	94328	-0.82	-0.94	-5.05
94323	94328	-0.82	-0.19	-3.25
94326	94324	0.78	1.85	3.17
94323	94326	-0.77	-1.06	-3.47
94324	94466	-0.71	-1.88	-1.68
94323	94466	-0.71	-1.15	-2.91
94324	95323	-0.67	-2.39	-1.97
95323	94323	0.61	1.58	1.60
94324	94462	-0.60	-1.81	-1.52
94462	94323	0.60	1.01	4.44
94324	94463	0.50	-1.52	1.05
94323	94463	-0.50	-0.72	-3.08
94325	94328	-0.49	-0.66	-1.91
94326	94325	0.48	1.69	1.04
94466	94325	0.47	1.82	0.57
94324	94327	-0.44	-1.52	-0.61
94461	94324	0.44	0.58	0.58
94323	94327	-0.43	-0.76	-0.53
94328	95322	0.43	1.65	0.58
94461	94323	0.43	-0.32	0.77
94326	95322	0.42	2.64	0.44
94466	95322	0.42	0.72	0.35
94328	94461	0.41	0.40	0.39
94325	94462	-0.40	-1.66	-0.39
94327	94325	0.40	1.36	0.81

Fig. 3 **Time series of 0000 UTC daily sea-level pressure differences (hPa) for Watarrka (94323) minus Alice Springs (94326) in August 2001. The lower curve represents the observed differences, and the upper curve the differences after allowing for a fictitious increment of -0.77 hPa.**

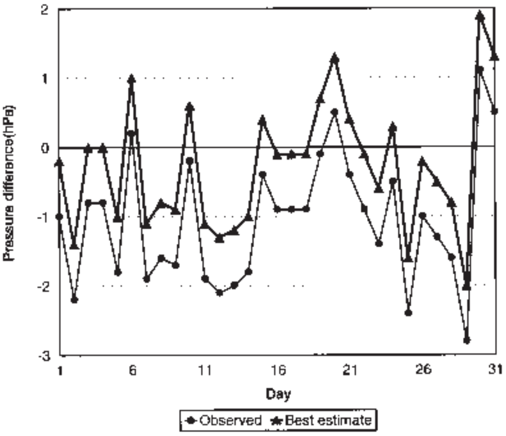
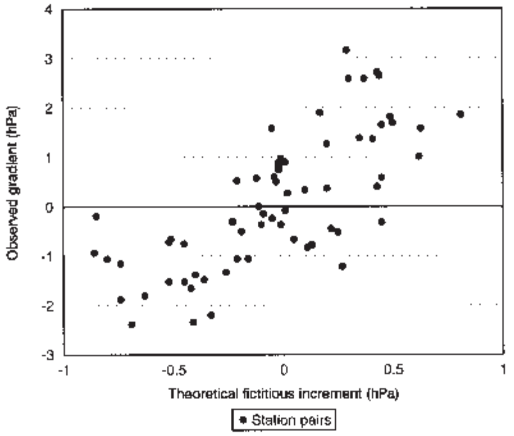


Fig. 4 **Observed monthly mean pressure differences (hPa) versus fictitious increments (hPa) for all station pairs at 0000 UTC during August 2001.**



force the prevailing mean pressure gradient. Otherwise expressed, the fictitious increments make the gradients too strong. A possible explanation is provided by Eqns 1 and 2 in the preceding section. These equations imply that, for two stations at the same height above sea level, the fictitious increment *d* to the pressure gradient is inversely related to the gradient of the mean virtual temperature used for pressure reduction. For most of the year, temperatures on average increase equatorward and pressures increase poleward, so the fictitious increments to the pressure gradients will tend to reinforce the existing gradients.

The spatial pattern of fictitious increments *d* is shown in Fig. 5. Arrows on the lines joining station pairs point towards higher pressure. Some lines have been omitted for clarity. While more arrows have components towards the south than to the north, this is not always the case, which suggests the explanation for reinforcement, provided in the previous paragraph, is only a partial one.

The values of the increments *d*, when integrated around triangles in Fig. 5, do not sum to zero, because the three stations forming a triangle are all at different heights. However, except where the station height differences are large, the sums are usually less than 0.20 hPa. This suggests that to a good approximation, the fictitious gradient increment values in Fig. 5 can be usefully transformed to equivalent bias values at station locations, analogously to using winds to produce a geopotential analysis. The specific algorithm to achieve this transformation utilises minimisation of a penalty function, and is described in the Appendix. The resultant bias values corresponding to the fictitious increments in Table 2 and Figs 3 and 5 are shown in Fig. 6. It can be verified that most differences between station locations in Fig. 6 correspond to within 0.20 hPa to the fictitious gradient increment values in Fig. 5. The values at station locations in Fig. 6 do not form a particularly coherent pattern, suggesting that the pressure biases corresponding to the fictitious increments are mainly on the scale of station separations.

The bias values in Fig. 6 may be compared with the 'apparent biases' calculated at all Australian stations as part of the routine monitoring of sea-level pressures by the Australian Bureau of Meteorology global data assimilation system. These apparent biases are the monthly averages, at each station, of the observed sea-level pressure minus the cross-validation pressure, where the latter is the analysed pressure at the station location without the use of the station being checked (Seaman 1999). The apparent bias is an exploratory tool to identify stations that may be spatially inconsistent with neighbours. The biases in Fig. 6, which are due only to fictitious increments, are compared in Table 3 with the apparent biases for August 2001. There is some correspondence between the two sets (9 out of 12 are of the same sign) but the correspondence is obviously far from perfect. Similar results occur in other months, and the overall correla-

Fig. 5 **Spatial pattern of fictitious increments (units: hundredths of hPa) for August 2001. Arrows point towards higher pressure. Some arrows are omitted for clarity.**

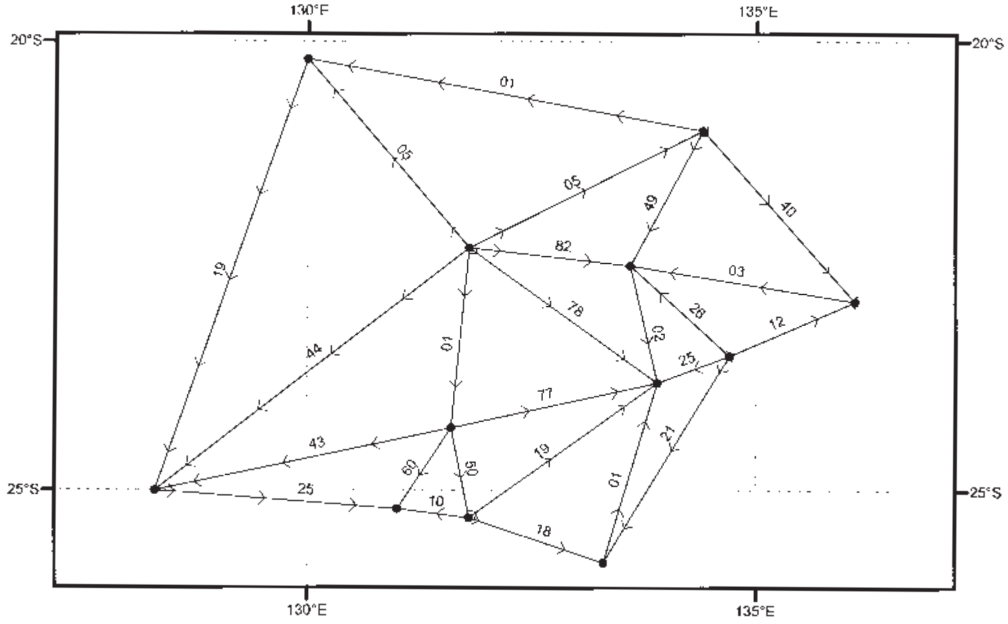


Fig. 6 **Biases corresponding to the fictitious increments in Table 2 and Figs 3 and 5. Units: hundredths of hPa.**

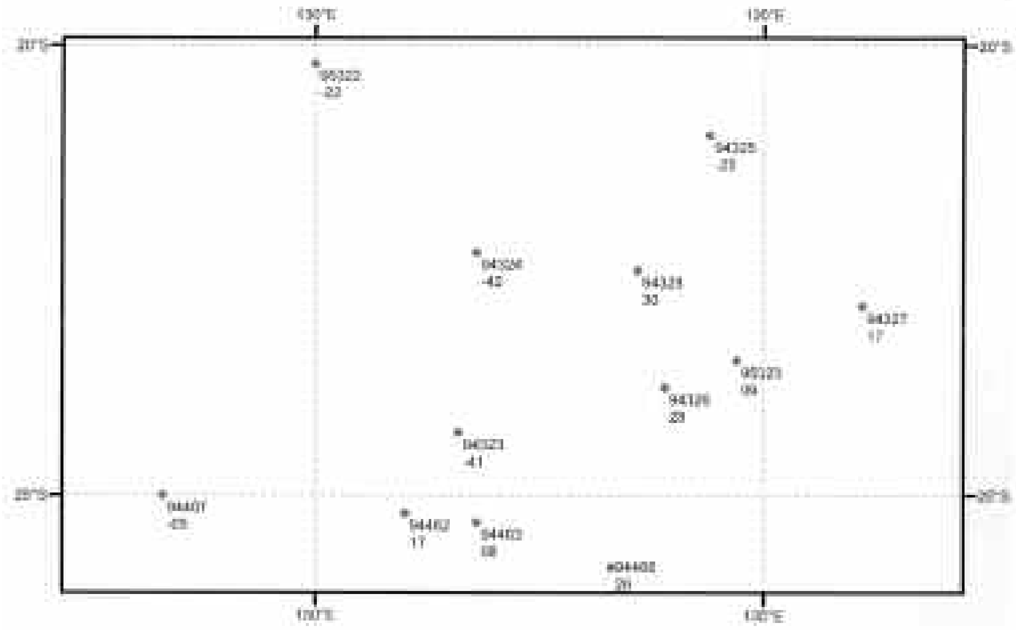


Table 3. Biases (hPa) corresponding to fictitious increments (as in Fig. 5), and apparent biases (hPa) from routine monitoring for August 2001.

Station	*Bias (hPa) corresponding to fictitious increment*	*Apparent bias (hPa) (all causes)*
94323	-0.41	-0.29
94324	-0.42	-0.47
94325	-0.25	-0.40
94326	0.28	0.05
94327	0.17	0.20
94328	0.30	0.00
94461	-0.05	-0.07
94462	0.17	0.11
94463	0.08	-0.31
94466	0.26	0.01
95322	-0.22	0.40
95323	0.09	0.97

tion between the two sets of biases over the 24 months (306 pairs) is 0.41 (95 per cent confidence interval 0.31-0.50). The apparent biases incorporate influences other than those of fictitious increments, the most important being (a) real biases (which the apparent biases are meant to detect), and (b) pressure reduction uncertainties due to the source illustrated in Fig. 1(a). Therefore, it is not surprising that the correlation between the two sets of biases is only moderately positive.

Possible uses of fictitious increments

Since fictitious increments occur at every observation time during a month, and can be calculated in advance, they may be of some use in improving analyses. One requirement of a sea-level pressure analysis is that the sea-level pressure gradients over elevated terrain should be well related to horizontal pressure gradients in the real atmosphere at the level of the topography. Therefore, the pressure gradients in the analysis should have the effects of the fictitious increments removed. For manual analyses, it might be sufficient for the analyst to be provided with a chart similar to Fig. 5, showing neighbouring station pairs for which the fictitious increments were greater than a threshold, such as 0.4 hPa. Alternatively, a chart like Fig. 6 could be provided. The analyst could then adjust the isobar spacing accordingly. As discussed earlier, such adjustments over central Australia would usually have the effect of relaxing the gradients implied by the original sea level pressure observations.

For numerical analysis in a data assimilation system, the situation is different. Ideally one might wish to assimilate surface pressure directly, and not use observed sea-level pressures at all, but this approach has its own practical problems (Ingleby 1995). However, if sea level pressures are used, they may be best used in pairs, as gradient information over plateau-like areas, with the gradients pre-corrected to remove fictitious increments.

For quality monitoring of sea-level pressures, an advance knowledge of fictitious increments may help to identify those stations where a large apparent bias is due to fictitious increment effects rather than to a bias in the barometer itself. For example, in Table 3, it would be reasonable to ascribe the apparent biases of -0.47 and -0.40 at stations 94324 and 94325 in part to the effects of fictitious increments, but it would not be reasonable to do so for the apparent bias of 0.97 hPa at station 95323.

Summary

The Australian method for pressure reduction from station level to sea level is based upon a monthly mean climatology. Consequently, over plateau-like areas, the fictitious pressure gradients introduced as an artifact of the reduction method do not vary much from day to day, and can be calculated in advance. The magnitudes of these fictitious gradients are of practical significance, and should be taken into account both for analysis and for quality control.

References

Colquhoun, J.R. 1965. A limited test of methods for pressure reduction to sea level. *Aust.Met.Mag., 49*, 28-39.

Gibbs, W.J. 1952. Notes on the reduction of barometer readings. *Aust. Met. Mag.,1*,1-6.

Hopwood, J. 1978. A trial of an empirical method of predicting tropical cyclone motion in the Western Australian region. *Aust. Met. Mag., 26*, 65-78.

IMSL 1994. *Fortran subroutines for mathematical applications*. Visual Numerics, Inc., 1141 pp.

Ingleby, N.B. 1995. Assimilation of station level pressure and errors in station height. *Weath. forecasting, 4*, 172-82.

Seaman, R.S. 1997. A comparison of some methods for reduction of pressure to sea level over Australia. *Aust. Met. Mag., 46*,15-25.

Seaman, R.S. 1999. Quality control of Australian sea-level pressure observations. *Aust. Met. Mag., 48*,123-31.

Appendix

Calculation of biases corresponding to the fictitious increments

Fictitious increments to the sea-level pressure gradients between all pairs of observing points are given, and equivalent pressure biases, that agree as closely as possible with the increments, are required at all observing points.

Define the increments as $((d_{ij}, i=1, j\text{-}1), j=2, N)$ where N is the number of observing points. Equivalent biases $(b_i, i=1, n)$ are required such that the penalty function

$$F = \sum_{j=2}^{N} \sum_{i=1}^{j-1} (b_i - b_j - d_{ij})^2$$

is a minimum.

The minimisation is performed iteratively by the Newton method, starting with all b_i equal to zero, and using the IMSL (1994) routine UMINF. Convergence to a root mean square agreement between b_i, b_j and d_{ij} of less than 0.10 hPa usually occurs within 10 iterations. By starting with initial estimates of zero, the sum of the final increments is constrained to zero.