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Trajectory calculations in support of meteorological planning and forecasting for two transcontinental balloon flights

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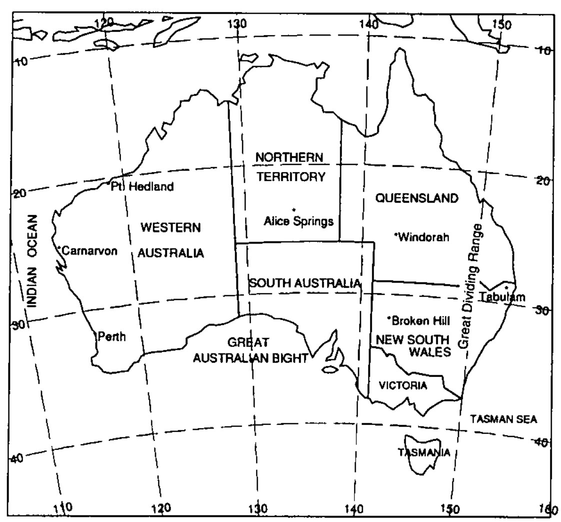
The meteorological advice provided during the planning and the flight phases of the two cross-Australia balloon flights during June 1993 is described. Both the planning and the forecasting phases of the advice used trajectory simulations based on wind fields from the Bureau of Meteorology limited area numerical weather prediction system. The trajectory forecasts made during the two cross-Australia balloon flights in June 1993 are compared with the actual flight paths of the balloons, and also with trajectories computed using analysed rather than forecast wind fields. Generally the forecast guidance is qualitatively good, but examples of uncertainty in the forecasts where strong horizontal and vertical wind shears are present near the point of origin are shown.

Introduction

During June 1993, two separate attempts to cross Australia using Roziere-type balloons (see *Australian Geographic* 1993) were made by teams led by Phil Kavanagh of Kavanagh Balloons, and Dick Smith of *Australian Geographic*. Both balloons were launched from Carnarvon (see Fig. 1 for all place names mentioned in the text) in Western Australia (WA), but at different times. The Kavanagh balloon was launched at dawn on 2 June and landed near Windorah in southwestern Queensland after some 42 hours flying time. The *Australian Geographic* balloon was launched around midnight on 16 June and landed east of the Great Dividing Range in northern New South Wales after a 40-hour flight.

The Bureau of Meteorology (BOM) was involved in the planning of these attempts, and also provided operational forecasts during the flights. The purpose of this paper is to describe some of the planning and operational forecasting techniques which were employed during this exercise. An important element of both the planning and forecast processes was the ability to simulate trajectories for a range of balloon altitudes and departure points using the package described by Mills and Powers (1990), modified to follow constant pressure levels. These simulations used both series of analyses to produce what might be termed 'perfect prognosis' or 'hindcast' trajectories, and also used forecast wind fields. The hindcast simulations were used to estimate the frequency of upper air patterns at different levels

Fig. 1 **Locality diagram.**



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likely to produce a successful transcontinental balloon flight in a time period of around three days from different locations in WA, and these results were used in selecting the launch site. Forecast trajectories were to provide guidance to the balloonists in flight as to their likely path at different altitudes. This, it was hoped, would enable the balloon pilot to adapt to changing circumstances as the flight progressed, and perhaps increase the chances of a successful transcontinental flight, and also help the planning of the recovery teams. Until the balloons actually took off, of course, there was no independent verification of these simulated trajectories, and as part of this paper the forecast trajectories will be compared with the actual paths taken by the balloons. While this paper will concentrate on the trajectory aspects of the planning and forecasting process, brief descriptions of the weather systems which occurred during these flights and some of their effects on the missions will be presented.

The next section of this paper will describe the methods by which forecast trajectories were computed, and the following section will describe some of the meteorological planning using these trajectories. The meteorological aspects of forecasting for the two balloon flights will then be described, and it is here that the trajectory forecasts will be compared with the balloons' paths.

Trajectory calculations

Both the analysis and the forecast data sets used to calculate the trajectories were produced by the BOM limited area numerical prediction system, RASP (Mills and Seaman 1990). The system has a horizontal grid spacing of 150 km and analyses geopotential height, wind components, temperature and dew-point depression, with a six-hour update cycle at 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100 and 50 hPa, using a six-hour forecast from the previous analysis as a first guess.

The forecast model uses the same horizontal grid, but has 15 vertical sigma levels (0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.78, 0.85, 0.9, 0.95 and 0.98). Analyses are archived every six hours on both the analysis pressure surfaces and on the model sigma surfaces. Thirty-six-hour forecasts are computed every 12 hours, and model fields from these forecasts are written to disc and archived at three-hourly intervals.

The trajectories are calculated from the equations:

$$\Delta x = u \, \Delta t$$
$$\Delta y = v \, \Delta t$$

using the Adams method (Hildebrand 1962, p. 97) to integrate the equations using a timestep of 1800 s. Wind components are interpolated horizontally using a bilinear interpolator, vertically using cubic splines, and linearly interpolated in time between six-hourly analysis or three-hourly forecast intervals. Previous published uses of this system (Mills 1989; Velden and Mills 1990) included the model vertical motion to provide three-dimensional trajectories. In the case of a gas balloon, constant pressure trajectories are more appropriate, and so the vertical equation was replaced with a specified pressure level.

Hitherto, no objective verification of these trajectories has been possible. There are potential errors associated with the horizontal resolution of the analyses, analysis error, the interpolation in the horizontal and in the vertical, and the lack of time resolution between the analyses. Kuo et al. (1985) reported a careful study where a high resolution primitive equations model was used to provide a 'perfect' set of trajectories. The spatial and temporal resolution of these data were then progressively degraded, and the increase in error of the computed trajectories was identified. This study showed a steady increase in error as the spatial and temporal resolutions of their data sets were reduced, however these results also indicate that useful qualitative guidance should be available from the spatial and temporal resolution of the RASP data sets for one to two-day trajectory computations.

Various strategies were used to make some subjective assessment of the reliability of the forecast trajectories, given that prior to launch no verification is possible. The first unknown was the level at which the balloons would be flown, as the pilot of a Roziere balloon has considerable altitude control. A spread of altitudes around a flight level indicated by the balloonists was selected to give some estimate of likely scenarios, and it was intended in the planning stages that the balloon pilots would be given this type of advice during their flight.

A second strategy was to compute trajectories from a small array of grid-points surrounding the starting point. If the balloon was in a broad, unsheared airstream, then it would be expected that the family of trajectories would be closely similar, indicating that small analysis error, or numerical errors in the integration along the trajectories, would not significantly affect the forecast accuracy. If, however, the balloon's initial position was in a strongly sheared environment, or near a 'node point' in the streamlines, one would expect to see considerably more divergence in the family of trajectories. This would then lead to less confidence in the forecast, as a small analysis error could lead to a large difference in the end point of the trajectory. This lesser confidence could then be communicated to the balloon pilot. Examples of these strategies will be presented in the following two sections.

Meteorological planning

The Bureau of Meteorology was approached by *Australian Geographic* in May 1993 with the following questions:

(a) How high would a balloon have to fly to have a reasonable chance of crossing the Australian continent in two to four days during winter? (A successful flight was defined as a departure near the WA coastline, and a landing anywhere east of the Great Dividing Range.)
(b) What launch site in WA would be most suitable for such an attempt?
(c) What typical surface synoptic weather pattern would indicate a successful flight was possible?

The trajectory package was used in a 'perfect prog' mode during this planning process, using a series of analyses at six-hour intervals out to 60 hours to compute trajectories from a series of grid-points extending northwards from near Perth to near Port Hedland along a model grid column, and at the 700, 600, 500, 400 and 300 hPa pressure levels. A typical simulation is shown in Fig. 2. These simulations were run each day from 1 June to 26 June 1992, and composite trajectory 'spaghetti diagrams' were prepared showing all paths from each given grid-point and level (see an example in Fig. 3). From this assessment the recommendation was that a balloon floating at 600 hPa and departing from between 25° and 30°S would have crossed the continent in approximately 2.5 days on about 50 per cent of the selected days. If the height of the flight was increased, then the duration of the flight would be less and the number of suitable days would be greater.

Fig. 2 Example of the trajectories computed during the planning phase. This example is for trajectories commencing at 2300 UTC 14 June 1992. Five grid-points have been selected, the flight level is 600 hPa, and the numbers show the time in hours along each path.

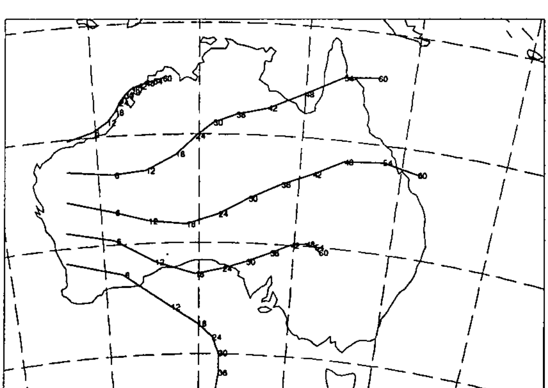
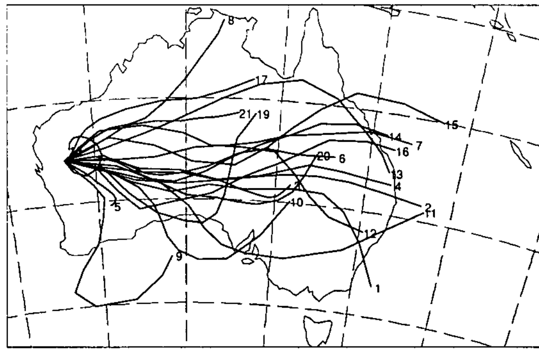


Fig. 3 A composite diagram showing potential flight paths of 60 hours duration at 600 hPa from a grid-point near 25°S for 21 days in June 1992. The figures at the end show the 2300 UTC starting date of each path.



Another requirement at the launch site is light surface winds to enable an easy filling and launch of the balloon. Climatological frequency tables indicated that very light winds overnight were the norm at Carnarvon during June. Climatological analyses indicated that a launch site near Carnarvon would best meet requirements for both upper and surface winds. Figure 4 shows the mean June MSLP and 500 hPa wind analyses for the 12 years from 1980 to 1991, computed by averaging the 250 km grid 'METANAL' archived regional analyses (see Seaman et al. 1977). At the surface the WA coastal region is in a col area between the anticyclones over the Indian Ocean and over the Australian continent, while at 500 hPa, the effects of the subtropical jet stream can be seen in the band of stronger winds over central Australia. A comparison of the June 1992 mean conditions (when the feasibility study was done), shown in Fig. 5, with the long-term mean (Fig. 4) shows that the mid-latitude trough southwest of WA was more pronounced than usual, with a slightly weaker continental anticyclone and rather stronger 500 hPa winds across the balloon's recommended flight corridor. Thus the recommendations based on that one month may have been somewhat optimistic.

Comparison of days on which successful trajectory simulations coincided with suitable synoptic weather conditions indicated that while there was considerable case-to-case variation, a typical pattern required a relatively straight upper-level jet over Australia, generally with a weak upper trough approaching the WA coast, and a relatively weak ridge extending east-west across Australia at the surface, with a well-established westerly airstream to its south.

Fig. 4 Average 1980–1991 June MSLP analysis (top, contour interval 2 hPa) and 500 hPa vector wind analysis with overlayed isotachs (bottom, contour interval 5 m s^{-1}).

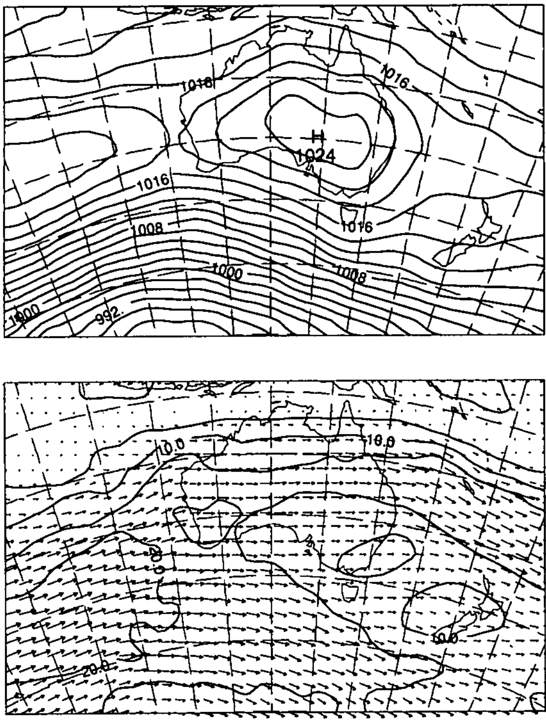
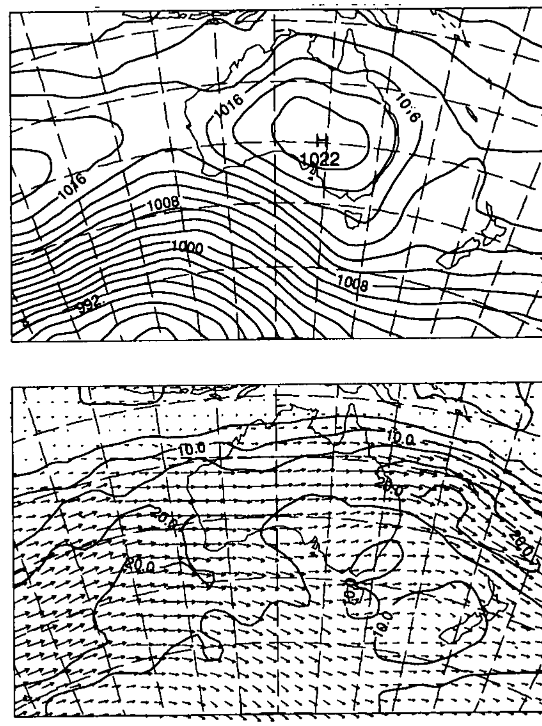


Fig. 5 Average 1992 June MSLP analysis (top, contour interval 2 hPa) and 500 hPa vector wind analysis with overlayed isotachs (bottom, contour interval 5 m s^{-1}).



Weather conditions over Australia in June 1993

The balloonists arrived in Carnarvon intending to launch their balloons at the first available opportunity after 1 June. At this stage a daily 'Balloon Briefing' was being prepared in the Bureau's National Meteorological Centre (NMC), and included a description of the current weather, a statement as to whether upper-level winds would be suitable for a successful flight leaving the following morning, and if so, whether surface conditions at Carnarvon overnight would be suitable for filling the balloon. An outlook of likely landing conditions and inflight weather was also given. The chief guidance material used here was the global and regional numerical weather prediction (NWP) products, with the WA Regional Forecast Centre (WARFC) providing advice on expected overnight surface weather conditions. These 'Briefings' were issued daily until the *Australian Geographic* flight ended on 18 June.

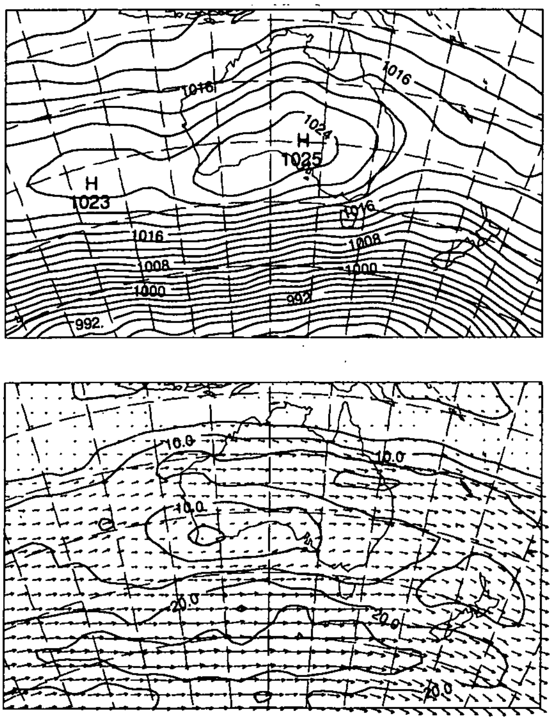
Once a forecast of weather suitable for takeoff was issued in the afternoon, a continuous watch was maintained in the NMC, and updated advice provided regularly to the launch teams in Carnarvon. 'Nowcasts' of surface wind were also provided for the first two or three nights by Noel Puzey of the WARFC, who was providing support in Carnarvon at that time.

While each flight was in progress, the *en route* weather and winds were continuously monitored, and the pilots were briefed at frequent intervals, communications links permitting. This service was provided from the NMC for the Kavanagh flight and from *Australian Geographic*'s 'Mission Control' for the *Australian Geographic* flight.

The mean MSLP and 500 hPa wind analyses for the first 18 days of June 1993 are shown in Fig. 6. This period shows large departures from climatology, with much higher than usual pressures over southern WA and the ocean area immediately to its south, and a marked split flow at 500 hPa. The wind maximum over northern Australia was stronger than normal, and was also displaced a little further north of the climatological position.

This synoptic pattern had several consequences for the attempted balloon flights. While the stronger than normal upper winds regularly indi-

Fig. 6 1–18 June 1993 average MSLP (top, contour interval 2 hPa) and 500 hPa vector wind analysis with overlayed isotachs (bottom, contour interval 5 m s^{-1}).



cated suitable upper-level wind conditions, the stronger than normal anticyclone south of WA produced stronger than normal surface winds over the launch site at Carnarvon, which regularly made filling the balloon impossible. This reduced the number of suitable launch dates well below that expected from the feasibility study. A practical consequence of this was a two-week wait by the *Australian Geographic* crew from 2 to 16 June for suitable surface conditions. Another consequence of these upper-level flow patterns was the occurrence of several northwest cloudbands (Downey et al. 1981) through the period.

The Kavanagh flight

This flight was launched at dawn on 2 June 1993, from Carnarvon (24° 53′S 123° 39′E), and initially headed northeast, before curving to the east and then east-southeast, finally landing near Cooper Creek, southwest of Windorah in western Queensland. The track of the balloon, based on the balloonists' Global Positioning System (GPS) records, is shown in Fig. 7, and the levels at which

Fig. 7 The track of the Kavanagh balloon. Date/time (UTC) are marked at intervals along the track.

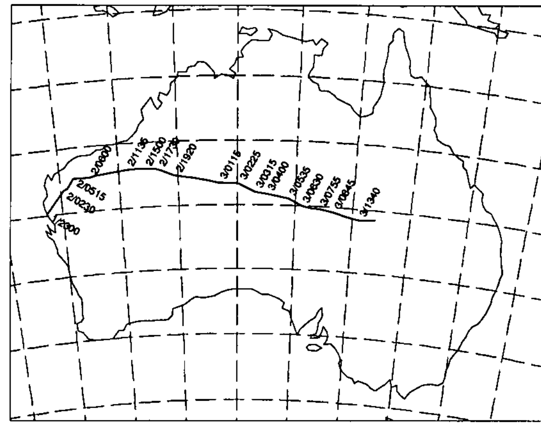
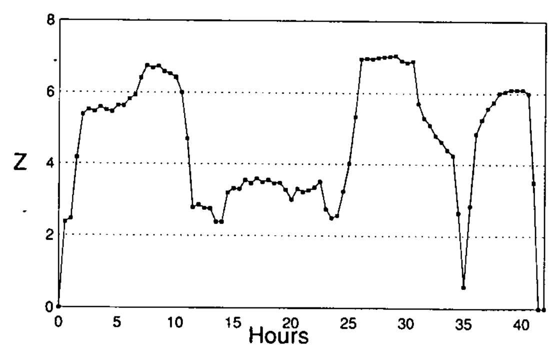


Fig. 8 Profile of flight level (km) versus time (UTC) for the Kavanagh balloon flight.



the balloon flew, based on their barograph records (to 30 hours) and navigational charts, are shown in Fig. 8. It can be seen that the balloon changed altitude dramatically during its flight, ascending to above 6500 m during the day, descending to around 3000 m during the first night, and showing marked changes in altitude as the balloonists experienced difficulties with cloud and icing before landing on the second night.

The MSLP and 500 hPa analyses at 2300 UTC 1 June are shown in Fig. 9 (local time is 10 hours ahead of UTC in eastern Australia, 8 hours ahead of UTC in Western Australia). The surface winds were the critical forecast here, as the previous night an attempt to fill the *Australian Geographic* balloon had to be aborted when a wind gust tangled the balloon. The surface winds were forecast to weaken as the southern trough passed

Fig. 9 Mean sea level pressure analysis (top) and 500 hPa vector wind analysis with overlayed isotachs at 2300 UTC 1 June 1993. Contour interval for MSLP 4 hPa, for wind speed 5 m s^{-1}.

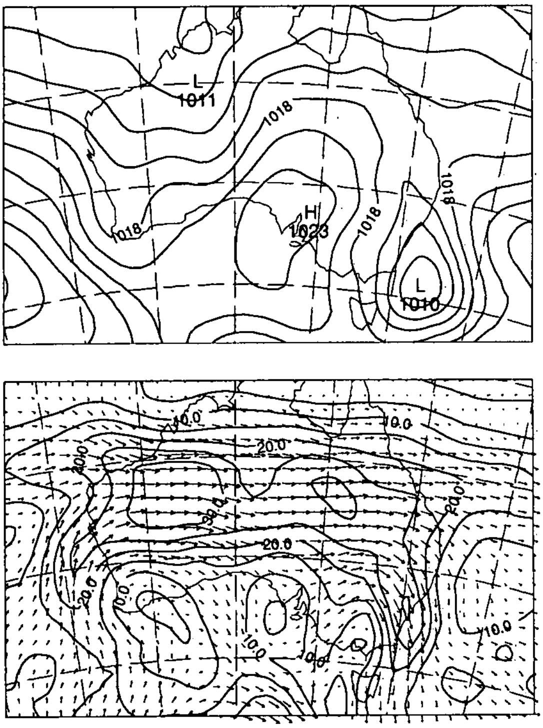
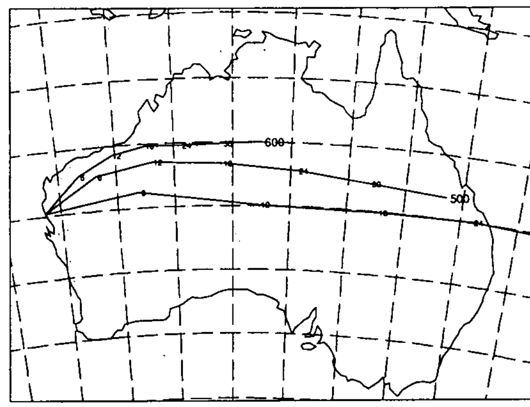
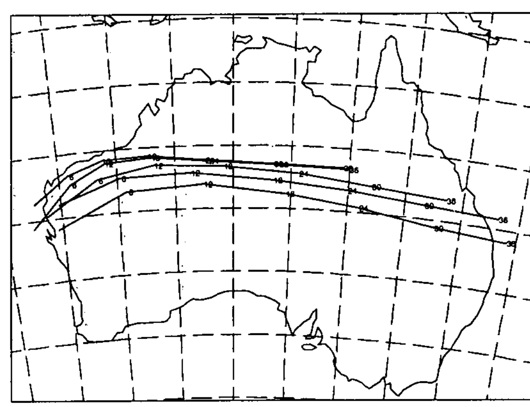


Fig. 10 (a) Thirty-six-hour forecast trajectories from Carnarvon at 2300 UTC 2 June 1993 at 600 hPa, 500 hPa and 400 hPa (top). (b) Thirty-six-hour forecast trajectories at 2300 UTC 2 June at 500 hPa from Carnarvon and from points 150 km northeast, southeast, northwest and southwest. The numbers indicate time in hours along the trajectory.

(a)



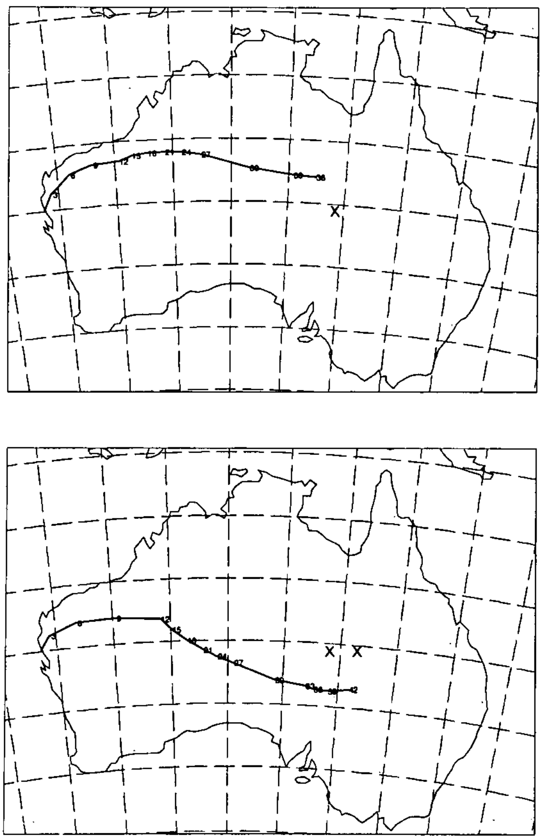
(b)



south of WA, and before the high re-established itself south of WA. While broadscale considerations indicated the slackening of the surface pressure gradient, surface wind conditions are so critical to balloon filling that the final decision to fill had to be made as a 'nowcast' at the launch site. Conditions were excellent for filling the balloon, and after launch it ascended into a broad band of strong winds (see Fig. 9). The balloon pilots indicated that they intended to fly between 500 and 400 hPa, and so a set of trajectory forecasts starting at 2300 UTC 1 June 1993 from the RASP 36-hour forecast based at that time were prepared from Carnarvon at 600, 500 and 400 hPa (Fig. 10(a)), with a 'grid array' ensemble (points at Carnarvon, and one grid-point northeast, northwest, southeast and southwest) shown for 500 hPa in Fig. 10(b). These all show the same general start to the northeast, followed by a curve towards the east-southeast. Given the observed increase in wind speed with height at these flight levels, the higher trajectories end further to the east, and all paths actually pass north of the final landing point: however, good general guidance as to the likely path of the balloon was provided by these forecasts, with the parallel clustering of the 'horizontal ensemble' trajectories giving good confidence in the forecasts.

The end point of the balloon's path is not well forecast by these trajectories: however, as Fig. 8 shows, a constant pressure surface is a very poor approximation to this balloon's true path. In order to assess the potential accuracy of our forecasts, a trajectory was calculated from the 36-hour forecast field and from the analyses valid at six-hour intervals, using estimated pressure altitudes along the balloon's path from Fig. 8. These forecasts are shown in Fig. 11. Each of these trajectories has its deficiencies, with the forecast position being somewhat to the northwest of the observed position, and the trajectory using analy-

Fig. 11 Forecast trajectories from Carnarvon at 2300 UTC 2 June 1993 using the best estimate of the balloon's pressure level from Fig. 7. Top, 36-hour forecast using forecast wind fields, X marks the balloon's position at 36 hours. Bottom, 42-hour hindcast using six-hourly analyses, Xs mark the 36 and 42-hour balloon positions.



ses being somewhat to the south. Sensitivity studies (not shown) indicate a very broad range of endpoints for a relatively small variation in elevation during the period when the balloon descended on the first night. It should also be noted here that this approach (specifying the elevation of the balloon) will compound any errors once the simulated balloon position differs from that observed.

As mentioned in the previous section, northwest cloudbands were a persistent feature in the first half of June 1993, and one was present when this balloon was launched. During the daytime hours of 3 June, with the balloon approaching Alice Springs, its track was just north of the main cloudband. The development of the cloudband over northern NSW and southern Queensland later that day, though, made the cloud impossible to avoid.

The *Australian Geographic* flight

The *Australian Geographic Flyer* was launched from Carnarvon at around 1500 UTC 16 June 1993, and followed the track and height path shown in Figs 12 and 13. The balloon landed near Tabulam, NSW (23° 53′S 152° 34′E), around 0715 UTC 18 June 1993. Figure 14 shows that at launch time at the surface a southern trough was passing southern WA, leaving the launch site in a col area. The 500 hPa pattern had changed dramatically from that experienced during most of the preceding two weeks, and the strongest mid-tropospheric winds were well south of the launch zone. Indeed, the winds at Carnarvon at 600 hPa were only just strong enough to make a launch possible. However, NWP guidance indicated that the winds should slowly increase and veer to the west-northwest over the launch site, and the 1100 UTC upper wind flight confirmed this trend. Accordingly the go-ahead for filling and launch was given. It is worth noting that following the change of circulation pattern, this flight encountered virtually no cloud.

Figure 15 shows the vertical and horizontal spread for forecast trajectories from Carnarvon starting at 1400 UTC 16 June (i.e. three hours into the 36-hour forecast based at 1100 UTC 16 June). While the trajectories leaving Carnarvon (Fig. 15(a)) show good correspondence with the observed track of the balloon, the horizontal

Fig. 12 The track of the *Australian Geographic Flyer* balloon. Date/times (UTC) are marked on the track.

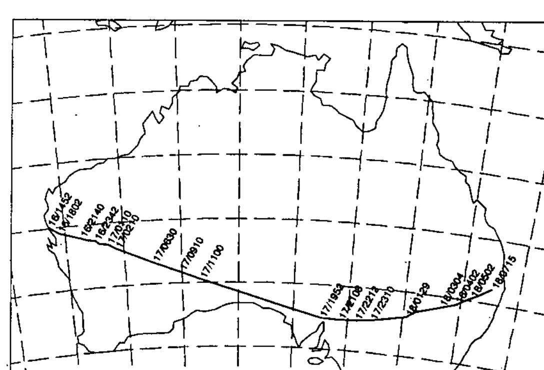


Fig. 13 Profile of flight level (km) versus time (UTC) for the *Australian Geographic Flyer* balloon flight.

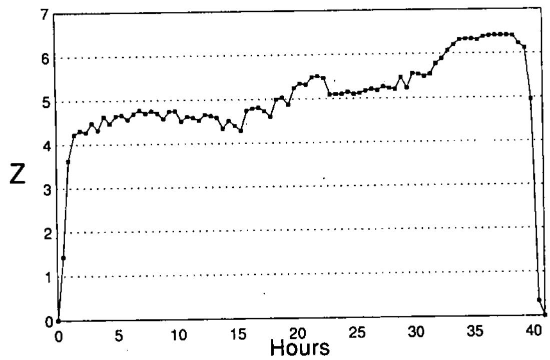
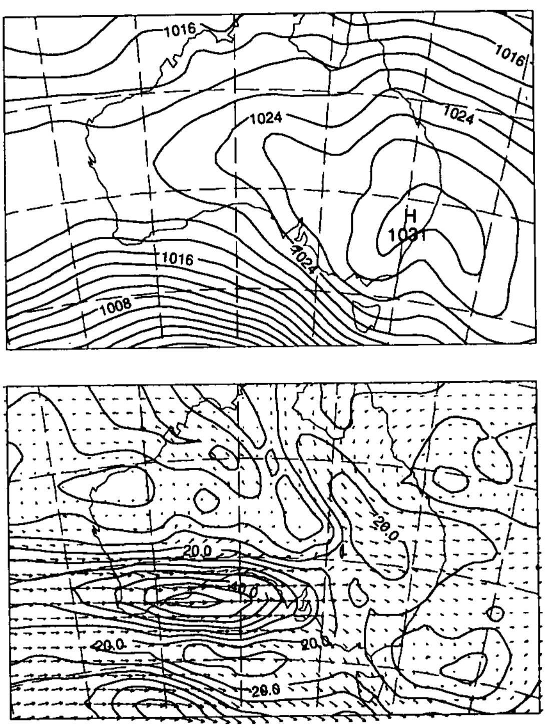


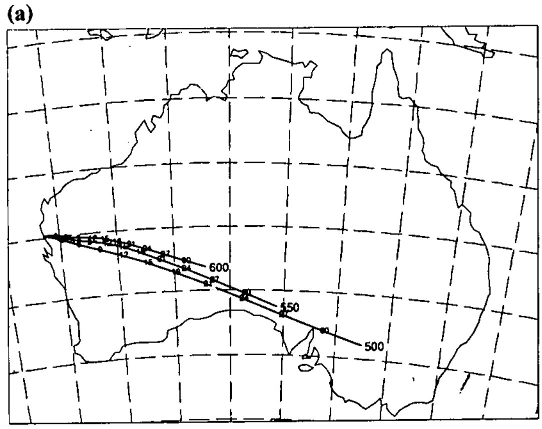
Fig. 14 Mean sea level pressure analysis (top) and 500 hPa vector wind analysis with overlayed isotachs at 1100 UTC 16 June 1993. Contour interval for MSLP 4 hPa, for wind speed 5 m s^{-1}.



ensemble forecast trajectories (Fig. 15(b)) show a great deal of spread, with endpoints of trajectories commencing 150 km northwest, northeast, southwest and southeast of Carnarvon covering an area over 15° latitude and 30° longitude after 33 hours. This is indicative of the marked horizontal wind shear at mid-tropospheric levels (see Fig. 14).

Fig. 15 (a) Thirty-three-hour forecast trajectories from Carnarvon at 1400 UTC 16 June 1993 at 600 hPa, 550 hPa and 500 hPa. (b) Thirty-three-hour forecast trajectories based at 1400 UTC 16 June at 550 hPa from Carnarvon and from points 150 km northeast, southeast, northwest and southwest.

(a)



(b)

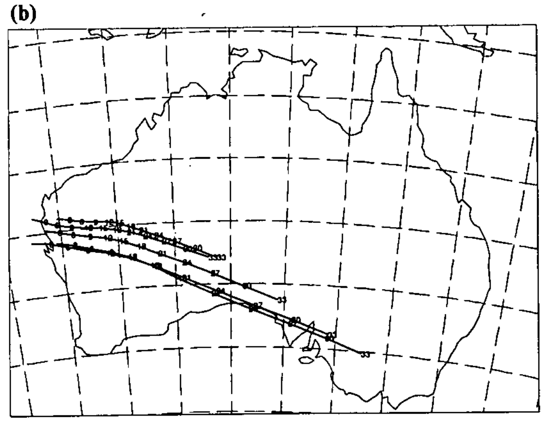


Figure 16 shows forecast trajectories from the balloon's position at 2300 UTC 16 June and at 1100 and 2300 UTC 17 June 1993. The left panels show the trajectories at 550, 500 and 450 hPa (approximately bracketing the balloon's observed flight levels), while the right-hand panel shows the spread of trajectories from the '5-grid-point-array' surrounding the balloon's position at 500 hPa. While there is a slight lack of meridionality in these trajectories compared with the observed track of the balloon, overall these are excellent forecasts.

On the morning of 18 June, with the balloon near Broken Hill, a decision had to be made whether to ascend to take advantage of stronger winds but take a longer path to the north, or to stay lower and follow a more direct route to the east. With the balloonists' decision to land before nightfall, our advice was to ascend, and the increase in the balloon's altitude for the last hours of its flight can be seen in Fig. 13.

Fig. 16 **Forecast trajectories from the balloon's position at 2300 UTC 16 June (top), 1100 UTC (middle) and 2300 UTC 17 June (bottom). The left panels show a vertical ensemble of trajectories at 550, 500 and 450 hPa, and the right panels show a horizontal ensemble of 5 grid-points at 500 hPa.**

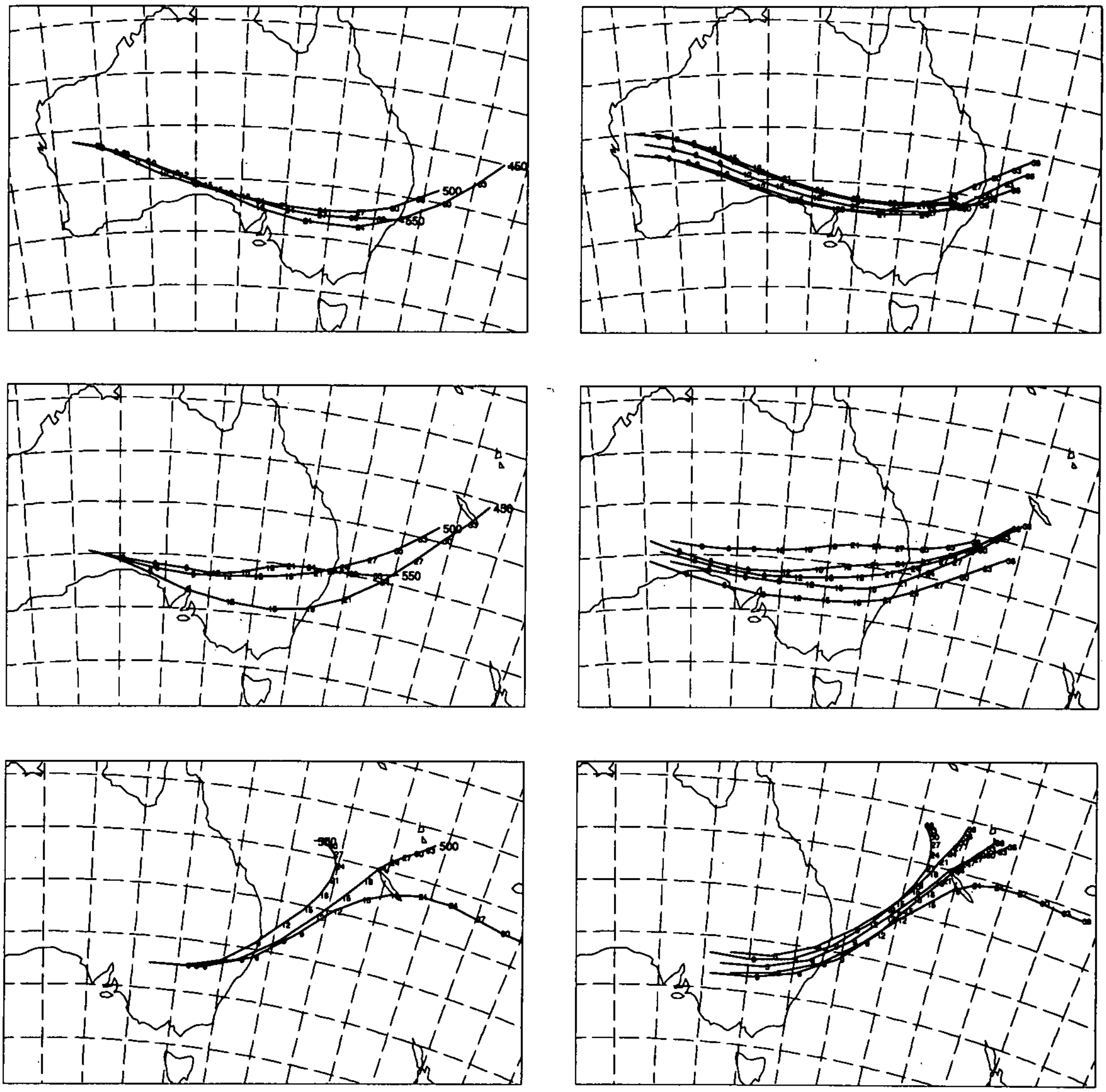
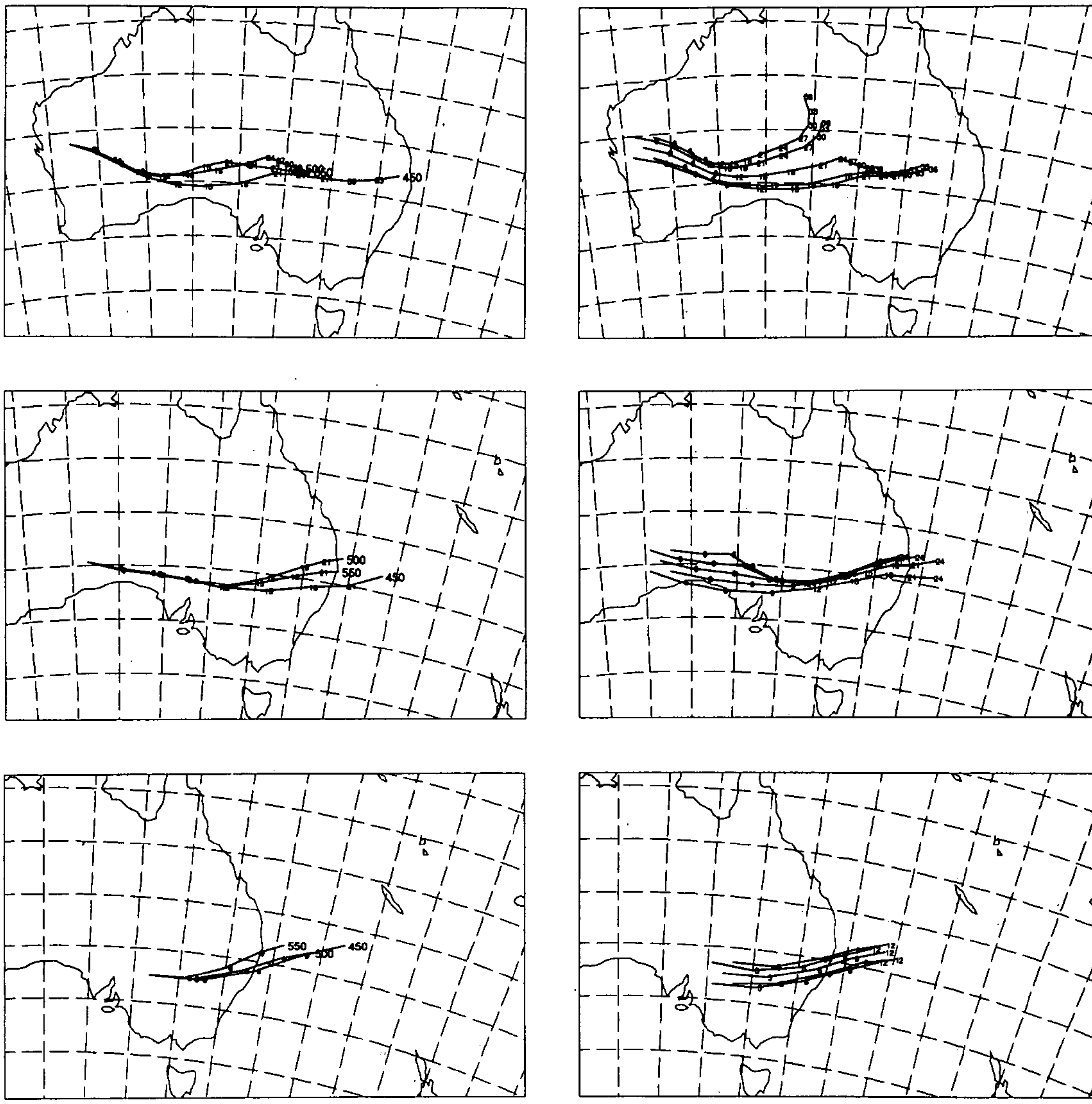


Figure 17 shows the same simulations as Fig. 16, but using analyses at six-hour intervals to provide the input wind fields. These trajectories are quite similar to those using the forecast fields for the second two times, but are rather worse for the first time. The horizontal ensemble simulation from 2300 UTC 16 June indicates that the trajectories from the analyses are just slightly closer to the northern edge of the band of strong winds than are the forecast trajectories, and so do not get 'caught' in the westerly stream. The reasons for this are not clear, and this point will be discussed further in the next section of this paper.

Discussion

The forecasts and hindcasts presented in this paper show that forecast trajectories on pressure surfaces provide excellent qualitative guidance on likely balloon paths for 36-hour periods in most of the (admittedly small number of) cases shown

Fig. 17 Hindcast trajectories using six-hourly analyses from the balloon's position at 2300 UTC 16 June (top), 1100 UTC (middle) and 2300 UTC 17 June (bottom). The left panels show a vertical ensemble of trajectories at 550, 500 and 450 hPa, and the right panels show a horizontal ensemble of five grid-points at 500 hPa.



here, except in those where the origin point is in a region of strong horizontal or vertical shear. This should give some confidence in the use of such trajectories for other studies. The sensitivity of the forecast trajectories to small changes in vertical coordinate, and in some cases to horizontal position (as in the early stages of the *Australian Geographic* flight), suggests that the horizontal and vertical ensemble strategy is very useful in providing a subjective estimate of confidence in the balloon's forecast path.

In several of the simulations there appeared to be a small lack of meridionality in the trajectories, and the forecast trajectories seemed to be slightly less in error than the hindcast trajectories in this regard. It is very difficult to ascertain the reasons for this, however the analyses do use non-divergent wind increments to add to the forecast fields, while the forecast fields are subject to vertical mode initialisation (see Mills and Seaman (1990) for more details), and this may mean that there is less cross-contour flow in the analysis data sets.

The errors occurred in accelerating or decelerating flow, which is consistent with this hypothesis. If this speculation is true, then increases in resolution and improved analysis systems currently in development may alleviate this problem. While some deficiencies in the simulated trajectories have been identified, the fact remains that on the continental scale, the balloons followed the paths indicated by the forecast trajectories, so long as the horizontal and vertical sensitivities of the forecasts were taken into account.

Acknowledgments

Many people crossed our paths or worked closely with us during the balloon expedition planning and operation. Their contribution was essential to the success of the BOM support of the two balloon flights. Bernie Shanahan, Paul Stewart and the shiftwork staff in the NMC provided sterling support at base camp, while Ed Green and Noel Puzey did the Bureau nothing but good at the WA end. Steve Symonds was indefatigable in Sydney, while Clive Edington, Mike Hassett, Mike Dalakis, Bruce Neal and Lee Hong all helped mightily with the hardware provided by the Bureau at *Australian Geographic*'s 'Mission Control' in Sydney. They are all gratefully acknowledged.

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