Evolution of the Bureau of Meteorology's Global Assimilation and Prediction system. Part 2: resolution enhancements and case studies

W. Bourke, T. Hart, P. Steinle, R. Seaman, G. Embery, M. Naughton and L. Rikus
Bureau of Meteorology Research Centre, Melbourne, Australia
(Manuscript received May 1994; revised September 1994)

This paper substantiates and discusses the progressive improvements in medium-range prediction skill resulting from enhancements to the horizontal and vertical resolution of the Australian Bureau of Meteorology's Global Assimilation and Prediction system (GASP). Resolution sensitivity experiments designed to measure the effects of an increase in prediction model resolution alone are described. The results of a parallel operational trial which led to the replacement of the wave 31, nine-level, univariate configuration of GASP by the corresponding wave 31, 19-level (R31L19) multivariate system are then presented. The operational R31L19, and experimental R53L19 predictions are compared with each other and with corresponding operational predictions, at still higher resolutions, from the European Centre for Medium Range Weather Forecasts (ECMWF) and from the US National Meteorological Center. Finally, two case studies, one a significant severe weather event, and the other a prediction of the spring 1993 stratospheric polar vortex, are shown to illustrate the current capabilities of the system.

Introduction

In part 1 (Seaman et al. 1994), recent improvements to the data assimilation and prediction model initialisation methods used in the Australian Bureau of Meteorology's Global Assimilation and Prediction system (GASP) were described. In this part, attention is focused upon improvements to medium-range prediction skill that are directly attributable to increases in horizontal and vertical resolution. Such resolution upgrades were made possible by the progressive upgrading of the Bureau's computing capacity between 1990 and 1993.

Following sections will describe: (a) sensitivity experiments designed to study the effect, upon medium-range forecasts, of enhanced prediction model resolution alone; (b) a parallel trial, during 1992, of the GASP wave 31, 19-level (R31L19) multivariate statistical interpolation (MVIS) assimilation system, versus the then operational R31L9 univariate (UVSI) system, which led to the former replacing the latter in 1992; and (c) further trials, during 1993, of the GASP R53L19 system that eventually led to its operational implementation in 1994. In (b) and (c), comparisons will also be made with the performance of global models from other operational centres. Finally, two case studies of special interest will be presented.
Resolution sensitivity experiments

To understand further the impact of system resolution on performance we examined the sensitivity of the prediction skill due to model resolution alone (as distinct from the improvement that might occur as a result of assimilating data at higher resolution). To explore specifically the sensitivity to model resolution we utilised high resolution analyses from the ECMWF for initial conditions. The initial conditions obtained from the ECMWF as spectral amplitudes at standard pressures (triangular truncation T106; 15 standard levels) were converted to the GASP model format with appropriate truncation and redefinition of sigma surfaces to match the topography representation used at the relevant resolution.

In implementing the 19-level version of the GASP prediction model some changes to the parametrisations of penetrative convection (Kuo 1974; Anthes 1977) and shallow convection (Tiedtke 1988) were made relative to the nine-level formulation described in Hart et al. (1990) and in Tada et al. (1989). In particular, partitioning of the moisture supply between moistening and heating was modified by choosing a value of 0.5 for the critical relative humidity in the Anthes (1977) formula for the moistening parameter. For layer relative humidity less than the critical value, the convergence of moisture contributes only to moistening, while for greater values both moisture and heating occur with moistening decreasing to zero as the layer approaches saturation. In addition, the diffusion coefficients associated with the shallow convection parametrisations were reduced by 50 per cent, and the shallow convective mixing is now also decoupled from the lowest model level. These changes were made to avoid an excessively active hydrologic cycle with the 19-level model in the tropics in particular. Finally, US real-time global sea-surface temperature analyses (Reynolds and Marisco 1993) replaced the previously used climatological temperatures.

The GASP model sensitivity to resolution was examined by comparison of R31L9, R31L19, R63L9 and R63L19 predictions initialised with ECMWF analyses for three initial conditions, namely 1200 UTC on 10, 12 and 14 January 1987. These analyses had been prepared as part of a study being sponsored by the Commission for Atmospheric Sciences/Joint Scientific Committee (CAS/JSC) Working Group on Numerical Experimentation on tropical prediction during the Australian Monsoon Experiment (AMEX). The anomaly correlation verifications of 500 hPa geopotential averaged over these three cases are shown in Fig.1(a) in both hemispheres for the four resolutions. All predictions are verified against the ECMWF analysis on a 3 x 3 degree grid. Although based on only three cases, the results suggest a substantial gain in performance with increasing horizontal and vertical resolution in the southern hemisphere. However, in the northern hemisphere at 500 hPa the most notable gain in performance comes from increased horizontal resolution. At 200 hPa (not shown) the positive impact of both horizontal and vertical resolution is quite marked in both hemispheres. An indication of the impact on prediction in the upper levels of the model is shown in Fig. 1(b) which shows the latitude-height plot of the bias error in temperature prediction at five days averaged for the three cases of R31L9 and R31L19 integrations. The reduction in error in the definition of the tropopause with the increased resolution is quite marked, with the tendency to overestimate the tropopause temperatures essentially eliminated. The implied representation of the stratosphere in the nine-level model is clearly inadequate with errors of −6°K and +7°K above and below the model level at approximately 70 hPa.

These results indicating potential gains in performance as a function of increasing resolution were becoming available as the design for the operational implementation of the global system incorporating MVSI was being developed. In defining this initial implementation it was decided on the basis of the positive results obtained at R31L19 and the then availability of computer time to mount a parallel operational trial of the system at that resolution, as described in the next section.

Parallel operational trial of the R31L19 MVSI system

The R31L19 MVSI assimilation and prediction system was run in parallel with the then operational R31L9 UVSI system for several months in the second half of 1992. It should be noted that the former system also utilised the incremental non-linear normal mode initialisation described in part 1, while the latter system employed the corresponding full field initialisation. Figure 2 shows the verification scores (S1, bias, root mean square (rms) error and anomaly correlation) of 500 hPa geopotential for the southern hemisphere annulus (20°-60° south) prediction to five days, averaged over the month of September 1992 for several systems. They are the upgraded R31L19 MVSI-based system (denoted as MV31), the then operational R31L9 UVSI system (G31), and the operational predictions from the ECMWF and from the US National Meteorological Center (NMC). The NMC results are from its aviation run (a rela-
Fig. 1 (a) Southern hemisphere (upper) and northern hemisphere (lower) anomaly correlation verifications of 500 hPa geopotential predictions between latitudes 20 and 60, at various resolutions, from ECMWF initial analyses and verified against ECMWF analyses; (b) latitude-height plot of temperature bias error (K) in five-day predictions at R31L9 (upper) and R31L19 (lower) resolutions. See text for details.

tively early data cut-off of about three hours in comparison to that of the Bureau (eight hours) and that of the ECMWF (13 hours)). Each prediction in Fig. 2 is verified against its own analysis. For all verification quantities the ECMWF T213L31 predictions are the most successful. However, of particular note is the approach of the R31L19 MVI-based predictions to those of the T126L18 results from NMC with in fact a reduced bias in the former. From the viewpoint of the Australian operations the most relevant result is the clear superiority of the R31L19 MVSI over the R31L9 UVSI system. Also included on the panels in Fig. 2 are error bars for the days three and five predictions, indicating the approximate standard error of estimate for the mean values presented. These were calculated from the standard deviation of the results over the month divided by the square root of the number of degrees of freedom n. To allow for the temporal correlation in the
Fig. 2 Anomaly correlation verifications during September 1992 of the southern hemisphere (20°-60° south) 500 hPa geopotential R31L19 MVSI-based predictions (denoted MV31), the US NMC predictions (NMC), and the ECMWF predictions (ECMW). The error bars for the day three and five predictions were computed as discussed in the text.

FIELD: 500MB GEOPOTENTIAL HEIGHT
REGION: 60.0S 20.0S 0.0E 360.0E SOUTHERN ANNULUS
(SEP 92) VERIFIED AGAINST OWN ANALYSIS

values, a time decorrelation length of five days was assumed, giving effectively only six independent samples (i.e. \( n = 6 \)) in computing the error bars. This seems a conservative procedure which should, if anything, overestimate the computed standard error. For simplicity in presentation, an average value over the individual experiments is presented. The error bars indicate that the impact at day three was highly statistically significant, especially for the rms and anomaly correlation measures. The day five results do not suggest very high significance in a formal statistical sense.

More extensive testing of the MVSI-based system was undertaken at higher resolution for a limited period of data assimilation from a period between 12 and 18 May 1992. Comparisons of predictions for five base dates from 1200 UTC May 14 to 18 were made for the following configurations:

(a) UVSI R31L9 denoted as G31;
(b) MVSI R31L19 denoted as MV31; and
(c) MVSI R53L19 denoted as MV53.

In addition NMC and ECMWF initial conditions were used to initialise the GASP R53L19 model as follows:
Fig. 3  (a) Anomaly correlation verifications of southern hemisphere (20°–60° south) 500 hPa geopotential predictions, against their own analyses, for the five sets of initial conditions detailed in the text. (b) Similar verifications of the US NMC operational predictions, and of the R53L19 predictions based on the NMC initial conditions. (c) Similar verifications of the ECMWF operational predictions, and of the R53L19 predictions based on the ECMWF initial conditions. (d) Similar verifications of all the R53L19 predictions (i.e. those based on MVSI and those based on the NMC and ECMWF initial conditions).

(d) NMC T126L18 initial conditions interfaced for prediction in the GASP R53L19 model, denoted as NG53; and
(c) ECMWF T213L31 initial conditions interfaced for prediction in the GASP R53L19 model, denoted as EC53.

The verification scores averaged for the five base dates for 500 hPa geopotential prediction in the southern hemisphere annulus (20° to 60°S) are shown in Fig. 3(a) for (a), (b) and (c), together with the verifications of the corresponding operational products from ECMWF and NMC. Again each prediction is verified against analyses of the originating system. Although based on only five predictions, the gain of the R31L19 system (MV31: the next to lowest curve in Fig. 3(a)) over the then operational R31L9 system is evident, although it is only at the resolution of R53L19 that the MVSI-based predictions match those of the T126L18 NMC system for this sequence of five predictions.
for May 1992. Figure 3(b) shows intercomparisons of the operational NMC predictions with the R53L19 predictions based on the NMC initial condition, Fig. 3(c) the intercomparisons of the ECMWF operational predictions with the R53L19 predictions based on the ECMWF initial condition, and Fig. 3(d) the intercomparisons of all of the R53L19 predictions (i.e. that based on MVSI and those based on NMC and ECMWF initial conditions). It is clear that truncation of the higher resolution ECMWF initial conditions to R53L19 reduces the prediction performance, but this reduction is less marked with the lower resolution NMC initial condition.

The ECMWF fields are generated operationally at T213L31 resolution in the model's hybrid sigma coordinate system. The fields used here as initial conditions had been interpolated to T106L15 standard pressure-level data. The T106 resolution is thus not fully matched by the R53 representation but the impact of truncating the ECMWF analyses is not the essential concern here; we are concerned with the quality of analyses available at the resolution we are able to implement (i.e. R53). The maximum loss of skill associated with this truncation in both the model and initial condition is suggested in Fig. 3(c) although differences here also reflect the differing model formulations as well.

The NMC Washington initial conditions here were obtained as spectral fields at the full model resolution of T126L18; in our processing they are interpolated to 15 standard pressure levels using the standard NMC (Washington) procedure for reduction of surface pressure to mean sea level. The spectral representation of these fields is then analysed without aliasing at R53L19. Again, the intercomparison here is to assess the quality of analyses available at the resolution of the BMRC system. The closer equivalence of results in Fig. 3(b) in comparison to the divergence seen in Fig. 3(c) reflects the overall superior performance of the much higher resolution system operationally available at ECMWF; the NMC resolution, while substantially higher than the R53 GASP system, is still well short of that used at ECMWF both horizontally and vertically. The near equivalence of all three R53L19 predictions (GASP, ECMWF and NMC) suggests the close agreement of the analyses from the various centres at this resolution in the GASP model.

On the basis of the results of the parallel trials from August to November 1992 the R31L19 MVSI global assimilation and prediction system was implemented operationally in the Bureau of Meteorology in December 1992. In continuing research, further evaluation of the R53 GASP system was undertaken as is described in the following.

**Assessment of the operational system, and further developments in 1993**

The R31L19 global MVSI-based assimilation and prediction system ran operationally from December 1992 to March 1994, with predictions to five days available from 0000 and 1200 UTC each day. A longer term perspective on the performance of this implementation of the Bureau's large-scale prediction system is seen in Fig. 4. Here we show the mean monthly S1 scores in the Australian region for 36-hour prediction of sea-level pressure for persistence, for the hemispheric R15L7 model that operated between 1976 and 1985, for the hemispheric R21L9 assimilation and prediction system (1985–1990), the global R31L9 UVSI system (1990–1992), and the R31L19 MVSI-based system (1993). Here the verification analysis is an independent analysis for the Australian region that has been operational since the early 1970s. Of note is the marked gain provided by the enhanced analysis component of the assimilation system introduced in 1985 as a hemispheric scheme (HASP, the predecessor to GASP), the ensuing gain with the R31L9 global system, and more recent gains with the R31L19 system. It is interesting to note that S1 scores of 55 for 36-hour prediction available in 1980–81 are now achieved at prediction ranges of from 96 hours onwards, i.e. a gain of at least 2.5 days in accuracy has been achieved in the regional prediction over the past decade with these numerical systems.

The operational R31L19 MVSI system was routinely verified and the anticipated improvements realised during 1993. It was also possible to trial an R53L19 MVSI-based system against the MVSI R31L19 system for much of 1993 as prelude to a further upgrade to this higher resolution in 1994. The comparison of the R53 and R31 system performances measures the combined effects, within the GASP system, of enhanced prediction model resolution, and of assimilation at higher resolution. The R53 option has become operationally feasible with the upgrade of the Bureau's Cray Y-MP in 1993 from a two to a three central processor facility. A substantial reprogramming of the global prediction model was undertaken to enable multitasking across the three processors. The revisions to model software for spectral transforms and overall model logic were designed to provide multitasking and reproducibility of calculation and are set out in the appendix.

The overall impact of the MVSI and of the increase in resolution up to R53L19, upon operational global analyses in the Bureau, is indicated in the global observation-fitting statistics of Table 1, which shows the rms statistics for mean
Fig. 4 The progressive improvement since 1975 of the S1 skill score of sea-level pressure predictions for the Australian region based on the Bureau's hemispheric/global NWP systems. See text for details.

The sea-level pressure averaged for February 1992 for the UVSI (R31L9) system and for February 1993 for the MVSI R31L19 and R53L19 systems. The improvements in six-hour first guess statistics between 1992 and 1993 is very clear, and the gain in data fitting of analysed and initialised fields is also quite apparent. With the increased resolution from R31 to R53 the rms statistics are further improved.

The performance at 500 hPa averaged over February, March and April 1993 is shown in Fig. 5 for the operational R31L19 system, along with the parallel trial at R53L19, and the operational predictions from ECMWF (T213L31) and from NMC (T126L18 aviation run). The error bars included on this figure were computed in the same way as those for Fig. 2. In the southern hemisphere (Fig. 5(a)) the results show that the ECMWF system remains the most successful prediction, with the operational MVSI R31L19 outperformed by NMC. However, the R53L19 system is competitive with the NMC system for this period. In the northern hemisphere (Fig. 5(b)) the superiority of the ECMWF system appears more marked, and while the R53L19 system shows gain over that at R31L19 the NMC results are noticeably superior to the R53L19. There is a suggestion in this intercomparison of hemispheric results and the relative performance as a function of resolution that the two high resolution systems of ECMWF and NMC deliver relatively more gain in the north than in the south. We speculate that a significantly superior representation of the topography in the northern hemisphere with the higher spectral truncation may be of more impact in northern hemisphere prediction. This speculation is consistent with resolution sensitivity studies conducted at the ECMWF where, for a 19-level configuration, the gains from enhancing horizontal resolution from T106 to T213 are minimal in terms of the southern hemispheric anomaly correlation but still significant in the northern hemisphere (Simmons 1992, personal communication). For the tropics the only wind fields available were those from the GASP system. The results shown (Fig. 5(c)) are typical of other levels and indicate that the increase in horizontal resolution alone appears to have little impact. This suggests that improvements in performance for the tropics will need to come from improved analysis and physical parametrisations.

The variability of performance over the Australian region within the months of February, March and April 1993 is shown in Fig. 5(d) by the time series of the S1 skill scores of mean sea-level pressure for 120-hour predictions. The performances of the systems from ECMWF, R31L19 and R53L19 are reasonably coherent with respect to prediction skill. In the practical use of the numerical products, the Australian region sea-level pressure predictions available from the various systems are closely examined by the operational meteorologists, and their synoptic assessments confirm the GASP system's consistency with the higher resolution ECMWF system. Although the error bars for 120-hour predictions in Fig. 5 do not indicate high formal statistical significance, Fig. 5(d) shows that within the considerable variability, the R53L19 system performs better than the R31L19 system in about two-thirds of the cases.

As part of our monitoring of the Bureau's R31L19 system, quantitative intercomparison of analyses and prediction error, both random and systematic, are made between the ECMWF and NMC systems, and the Bureau system for April 1993. The left frames of Fig. 6 show the monthly mean 500 hPa geopotential analysis difference

---

Table 1. Global rms fitting statistics (hPa) for sea-level pressure observations averaged over February 1992 for the UVSI R31/L9 system, and over February 1993 for the MVSI R31/19 and R53/19 systems (1200 UTC).

<table>
<thead>
<tr>
<th>System</th>
<th>First guess</th>
<th>Analysis</th>
<th>Initialised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 92 R31/L9 Univariate</td>
<td>2.44</td>
<td>1.47</td>
<td>1.66</td>
</tr>
<tr>
<td>Feb 93 R31/19 MVSI</td>
<td>1.82</td>
<td>1.16</td>
<td>1.41</td>
</tr>
<tr>
<td>Feb 93 R53/19 MVSI</td>
<td>1.71</td>
<td>1.02</td>
<td>1.29</td>
</tr>
</tbody>
</table>
Fig. 5 Verifications from February to April 1993, of predictions from the Bureau's operational MVSI R31L19 system (denoted GASP), the Bureau's MVSI R53L19 system (R53), the US NMC aviation run (NMC), and the ECMWF system (ECMWF). All predictions were verified against their own analyses: (a) anomaly correlation for 500 hPa geopotential for the southern annulus 20°-60°S; (b) anomaly correlation for 500 hPa geopotential for the northern annulus 20°-60°N; (c) rms error for 250 hPa zonal wind speed over the tropics 30°S-30°N; (d) the day-to-day variation of the sea-level pressure S1 skill scores over the Australian region for GASP, R53 and ECMW over the same period. The error bars on frames (a) to (c) were computed as described in the text.

(i.e. bias) between NMC and ECMWF, between GASP and NMC, and between GASP and ECMWF, and the right frames show the corresponding monthly mean of the rms differences in these analyses. A comparison of the two lower frames of Fig. 6 with the other frames indicates that there is closer agreement between the ECMWF and GASP analyses both in the mean and with respect to rms. It is possible that the early cut-off of the NMC assimilation system contributes to the greater discrepancies relative to the other two systems, and it would be of interest to confirm this by intercomparison with the NMC late cut-off results, although this aspect has not been investigated. The preceding comparison perhaps highlights the value of the later data cut-off in the southern hemisphere and suggests that the impact of this sensitivity should be further clarified.

Figures 7(a) to (d) show the 500 hPa geopotential fields of the following from the GASP R53L19 system:
(a) mean of the 1200 UTC analyses for the period 6 April to 5 May 1993;
(b) mean of the five-day predictions from all the analyses in (a);
(c) mean of the rms prediction errors in five-day prediction from all the analyses in (a); and
(d) mean prediction error (i.e. bias) in five-day prediction for all the analyses in (a).

Figure 8 shows the same fields as in Fig. 7 but for the ECMWF T213L31 system. The mean analyses and mean five-day predictions shown in (a) and (b) of Figs 7 and 8 display considerable similarity although the R53L19 systematic error is rather larger than that in the ECMWF system. However, it is interesting that the mean rms error in (c) of each figure indicates a slightly smaller area enclosed by the 80 m error contour in the R53L19 system indicating that the latter system has the lower random error. These interpretations are consistent with the rms error and bias results from our routine daily verification system (not shown).
Fig. 6 The April 1993 monthly mean (left frames) and rms (right frames) differences (metres) of 500 hPa geopotential between the Bureau's MYSI R53L19 and NMC (top), NMC and ECMWF (middle), and MYSI R53L19 and ECMWF (lower). For the mean difference charts stippled areas are greater than +20 m, shaded areas less than −20 m; for the rms charts shaded areas represent values greater than 10 m.
Case studies

In preceding sections we have presented substantial material quantifying the performance of the assimilation and prediction system as a function of recent enhancements. In the course of these studies we have of course also examined predictions in terms of synoptic performance. Two case studies of particular interest follow, one for a quite significant weather event during August 1992 and the other an example of prediction of the polar vortex in September 1992.

Adelaide floods in August 1992

This case was examined during the operational trials of the R31L19 MVSI-based system in relation to the then operational R31L9 UVSI system. In addition, the case has been re-examined with the MVSI system utilising R53L19 resolution, and here we compare the relative performances of all these systems.

The case concerns severe weather that occurred in the Adelaide (35° south; 139° east) region on
29 and 30 August 1992. During this period, downpours in the nearby Mt Lofty Ranges produced flash-floods that resulted in the loss of two lives. The synoptic evolution of this situation from 24 to 29 August is shown in Fig. 9. A small low pressure system southwest of Western Australia on 26 August was moving around the western side of a larger scale, amplifying trough in the Southern Ocean. On 27 August the larger scale system had reached peak intensity, with the smaller system now to the northwest. By 28 August the Southern Ocean trough began to weaken and move to the southeast, as the smaller feature intensified south of the Bight. On 29 August, the small-scale system continued to intensify and became the dominant system, with an associated thermal low almost directly over Adelaide. This cold outbreak is an extreme case, with the tropopause above Adelaide descending to almost 500 hPa at 2300 UTC on 29 August.
Fig. 9 The R31L19 MVSI analyses of sea-level pressure (solid lines) and 1000–500 hPa thickness (dashed) at 1100 UTC, 24 to 29 August 1992. The differences between the R31L9 UVSI, the R31L19 MVSI, and the R53L19 MVSI analyses are visually very small.
The 120, 96, 72, and 48-hour forecasts produced by the then operational R31L9 UVSI and the R31L19 MVSI systems for 29 August, shown in Figs 10 and 11, clearly demonstrate the superiority of the latter system. At five days (i.e. the forecast starting from 24 August) neither system gave particularly good forecasts. The UVSI system produced a trough in the Tasman Sea, with a high pressure centre in the Bight extending a ridge over most of southeastern Australia. The corresponding forecast from the R31L19 MVSI system was marginally better in that there was a small trough over eastern New South Wales/Victoria, and a high west of Western Australia extending a ridge into northern South Australia. At four days lead time, the UVSI system was little changed, except that the trough in the Tasman was somewhat deeper. The R31L19 MVSI system on the other hand was dramatically different, producing a low pressure centre near 42°S, 140°E and a high centre in the Tasman. While the general location of the major features was reasonable, the intensities of both the high and the low were excessive. The high was approximately 10 hPa too strong and the area covered by the low extended about six degrees of latitude too far west. The three-day forecasts are particularly interesting, in that the UVSI system still predicted ridging across South Australia and a broad trough over the Tasman and New Zealand. The R31L19 MVSI system, however, predicted a cut-off low centred east of Mt Gambier (38° south, 141° east). While this forecast position was still to the east of the verifying position it is obviously a far better forecast than that.

Fig. 10 The UVSI R31L9 predictions to 120, 96, 72, and 48 hours, all verifying at 1100 UTC, 29 August 1992.
Fig. 11 As in Fig. 10, for the MVSI R31L19 predictions.

from the UVSI system. The 48-hour forecasts are closer to each other and to the verifying analyses, although the UVSI system overforecast the strength of the trough in the Tasman Sea. Furthermore, the involuted thermal structure to the south of the continent was still poorly forecast. The 48-hour forecast from the R31L19 MVSI system was similar to the 72-hour forecast, the main difference being higher pressures in the eastern Tasman. The 24-hour forecasts from the two systems (not shown) were both quite close to the verifying analyses.

The preceding experiments compared the joint effect of a change in vertical resolution and a change in the assimilation method from UVSI to MVSI. We also examined for this particular case the impact of the change to the assimilation method alone by utilising a 9-level version of the MVSI assimilation system which was run from 20 to 30 August. The resulting R31L9 MVSI-based forecasts (not shown) were much closer to the operational UVSI R31L9-based forecasts than to the R31L19 MVSI-based forecasts. It therefore appears that in this case at least, the impact of vertical resolution was more important than the change from UVSI to MVSI.
Fig. 12 As in Fig. 10, for the MVSI R53L19 predictions.

Having substantiated the impact of vertical resolution we were also able to assess the impact of higher horizontal resolution, as R53L19 MVSI analyses and predictions were also available for the period. The two, three, four and five-day forecasts for 1100 UTC on 29 August are shown in Fig. 12. The R53L19 forecasts show further improvement over the R31L19 forecasts, with the 72-hour forecast position of the low southwest of Mt Gambier being very accurately forecast. There was also a slight improvement of intensity, with the central pressure forecast to be 2 to 3 hPa deeper. Moreover, a definite upper level cut-off was forecast at 72 hours by the higher resolution system. Since most of this development occurs over the ocean, the improvement due to increased horizontal resolution tends to indicate that there is still some information within the high resolution satellite data that is not being utilised by the R31L19 system.

The best-resolved global assimilation and prediction system has therefore been shown to provide significant improvements in forecast skill during a period favourable to the development of severe weather. While not capturing the finer detail of the storms, the forecasts three to four
days before the event gave good indications as to the likelihood of severe weather. The improvement relative to the then operational UVSI system was very clear.

Prediction of the spring polar vortex

A significant aspect of southern hemisphere meteorology in the past decade has been the now widely known loss of ozone during the Austral spring in the lower stratosphere. The loss of ozone in the Austral spring is strongly influenced by the dynamics of the polar vortex which acts to contain the particularly cold air which is conducive to the formation of polar stratospheric clouds and associated chemical destruction of ozone. Of particular relevance in the present context is the performance of the assimilation and prediction system in supporting the monitoring and prediction of the flow regimes in the stratosphere which so impact on the redistribution of ozone and on the depletion of ozone. One aspect of the recent upgrades, as noted earlier, is the increase in vertical resolution of the system; the current 19-level system now has six levels in the upper atmosphere (pressures less than 150 hPa; i.e. \( \sigma = 0.150, 0.100, 0.070, 0.050, 0.030, 0.010 \)) whereas the earlier nine-level system carried only two such levels. The impact of this increase in vertical resolution in the upper levels of the system has already been alluded to in the earlier discussion of Fig. 1(b) showing that systematic prediction error as a function of vertical resolution has been significantly reduced in five-day temperature predictions.

With the availability of the 19-level system we have followed the behaviour of the polar vortex rather closely and have provided the output for Bureau stratospheric ozone monitoring on the basis of the known correlation of the isotropic potential vorticity (IPV) in the stratosphere with the ozone distribution. Our first examination was during the parallel trial prior to operational implementation in December 1992 of the R31L19 MVS1 system. It now appears that the 1992 Antarctic ozone hole has been assessed as more extensive than in any previous year. The lowest latitude reached by the ozone hole boundary (taken as the 220 Dobson Unit contour) was measured over southern South America during 4 to 5 October 1992. The sequence of GASP R31L19 analyses of IPV on the 500 K isentrope for the period 29 September to 4 October are shown in Fig. 13 at daily intervals. The edge of the circumpolar vortex is clearly delineated and it is seen that the initial wave number three pattern, somewhat eccentric with respect to the pole, rotates and elongates into a wave number two pattern with high IPV air approaching southern South America on day five of this sequence, i.e. 4 October. The evolution over this five-day period is rather well captured in the five-day prediction from the 29 September initial condition as is shown in the sequence at daily intervals from the R31L19 model integration in Fig. 14. Corresponding to these sequences of dynamic analyses and predictions we show in Fig. 15 the US National Aeronautics and Space Administration (NASA) satellite total ozone retrievals for the same period. The delineation of the circumpolar vortex edge and sharp decrease in total ozone amounts is very evident in these ozone measurements. The correlation of the analysed IPV definition of the vortex edge and the ozone distribution is also very marked throughout the five-day sequence. We see then that the prediction of IPV as shown successfully captures the evolution of analysed IPV and the closely correlated ozone distribution. Similar levels of performance have been seen throughout the spring of 1992 and more recently during the spring of 1993. A related study of extended-range prediction for the stratosphere and the correlation of predicted IPV changes with changes in total ozone amount is currently underway. These predictions for the stratosphere are now routinely available from operations and are used in the daily monitoring and assessment of the behaviour of the stratosphere particularly during the springtime vortex breakdown.

Concluding remarks

The preceding results, in part 1 and in this paper, demonstrate the progressive improvements in the quality of data assimilation and of prediction skill of the Bureau of Meteorology's global assimilation and prediction system, due to refinements in the methodology for objective analysis and model initialisation, and to enhancements in vertical and horizontal resolution. The accompanying upgrades in quality control and data monitoring also contribute significantly to overall system performance. At the time of preparation of these papers in March 1994, the GASP system had just been implemented in operations at the resolution of R3L19 and the predictions extended to seven days for both the 0000 UTC and 1200 UTC predictions run each day. With the most recent operational R53L19 implementation we have calculations which are closely matched to the available Cray Y-MP 3/32 computing power and memory, and to the required operational schedules. A short-term upgrade is close to implementation through the use of a statistical interpolation in the assimilation moisture analysis rather than the long-used successive correction analysis. In the immediate future we anticipate a particular focus on enhancing the data base used in the assimilation system
Fig. 13 The analysed IPV on the 500 K isentropic surface, at 1200 UTC, 29 September to 4 October 1992 (units = K m² kg⁻¹ s⁻¹, scaled by 10⁵).
Fig. 14  The R31L19 model predictions of IPV corresponding to the fields in Fig. 13.
Fig. 15  The NASA total ozone retrievals (Dobson Units) corresponding to the fields in Fig. 13.
which remains less extensive than that used by a number of global systems in the northern hemisphere. In particular the satellite temperature retrievals are utilised in other centres at a resolution of 120 km whereas current availability in GASP is restricted to 250 km resolution. Current studies are focussing on (a) evaluating the impact of utilising the higher resolution soundings and on (b) improving the quality of the retrievals through using the GASP first guess temperature fields to perform physical retrievals from clear-column radiances routinely available from NMC Washington.

Major global assimilation and prediction systems in the northern hemisphere are now using global variational analysis algorithms (NMC, see Derber and Parrish (1992); ECMWF, see Heckley et al. (1992)). These approaches offer an integrated method of analysis for both conventional data and satellite-measured radiances. These schemes in three dimensions are a prelude to a four-dimensional approach. Within the GASP framework our plans for three-dimensional variational assimilation are focussing on applying these algorithms to the local but large data volumes as used in the MVS1 software. Our principal concern here is to ensure that we optimise the use of the satellite soundings and future types of satellite data in the southern hemisphere given their significant impact on medium-range prediction in the southern hemisphere.

Monitoring of the GASP system in absolute terms and relative to results from major operational centres in the northern hemisphere will be continued. The verifications of model performance have highlighted the progress in medium-range prediction achieved with the GASP system; the extension of the predictions to seven days has been based on initial synoptic and quantitative assessments which indicate useful extensions in range and accuracy have been achieved with the new R33L19 system.

Acknowledgments

The authors gratefully acknowledge the support of their colleagues in operations in the Bureau's National Meteorological Centre throughout the parallel operational trials and implementations of the recent GASP systems. Extensive programming support has been provided by Tan Le, Tony Bevan and Paul Mullermeister. The provision by Roger Atkinson of the figure displaying the ozone distribution is gratefully acknowledged.

References


Appendix

The spectral formulation developed by Bourke (1972, 1974, 1988) has been modified to yield in particular more efficient associated Legendre transforms. This reformulation was being considered at the time of implementing a multitasked version of the model and the opportunity was taken to implement transform algorithms that are both more efficient and more suitable for the multiprocessor facility.

Efficiency

The vorticity-divergence formulation of the primitive equations requires transforms from spectral (spherical harmonic) coefficients to gridpoint values and vice versa to spectral coefficients. In flux form the grid to spectral transforms for calculating the spectral coefficients of the right-hand side or tendency terms involve taking the horizontal curl and divergence of the nonlinear combinations computed on the grid. Efficiency gains have been made in the number of Legendre transforms required by rearranging the calculations in these derivative operations.
As in Bourke (1988) the evolution equations for vorticity and divergence are written as

$$\frac{\partial \zeta}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ \frac{\partial A}{\partial \lambda} + \cos \phi \frac{\partial B}{\partial \phi} \right] + \ldots \quad \text{1}$$

$$\frac{\partial D}{\partial t} = \frac{1}{\cos^2 \phi} \left[ \frac{\partial B}{\partial \lambda} - \cos \phi \frac{\partial A}{\partial \phi} \right] + \ldots$$

with the definitions of the variables as in Bourke (1988), and in this and subsequent formulae denote additional terms not relevant to this discussion. Similarly, the temperature and moisture equations have the form

$$\frac{\partial T}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ \frac{\partial}{\partial \lambda} (UT') + \cos \phi \frac{\partial}{\partial \phi} (VT') \right] + H + \ldots$$

$$\frac{\partial q}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ \frac{\partial}{\partial \lambda} (Uq') + \cos \phi \frac{\partial}{\partial \phi} (Vq') \right] + I + \ldots$$

where

$$H = T'D + q'\gamma + RT_{/c_p} \left[ \vec{D} + \vec{V} + \vec{V} \cdot \nabla \Pi \right]$$

$$I = q'D - \cos \phi \frac{\partial}{\partial \sigma}$$

These equations can be written in terms of corresponding expansions of appropriate Fourier coefficients (the tilde symbol signifies the variable is a Fourier coefficient, subscript \( m \) denotes the Fourier wave number):

$$\frac{\partial \bar{\zeta}_m}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ im \bar{A}_m + \cos \phi \frac{\partial \bar{B}_m}{\partial \phi} \right] + \ldots$$

$$\frac{\partial \bar{D}_m}{\partial t} = \frac{1}{\cos^2 \phi} \left[ im \bar{B}_m - \cos \phi \frac{\partial \bar{A}_m}{\partial \phi} \right] + \ldots$$

$$\frac{\partial \bar{T}_m}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ im(\bar{U}'_T)_m + \cos \phi \frac{\partial}{\partial \phi} (\bar{V}'_T)_m \right] + \bar{H}_m + \ldots$$

$$\frac{\partial \bar{q}_m}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ im(\bar{U}'q)_m + \cos \phi \frac{\partial}{\partial \phi} (\bar{V}'q)_m \right] + \bar{I}_m + \ldots$$

The Fourier space temperature equation can be rewritten as

$$\frac{\partial \bar{T}_m}{\partial t} = -\frac{1}{\cos^2 \phi} \left[ (im(\bar{U}'_T)_m + \cos \phi \frac{\partial}{\partial \phi} (\bar{V}'_T)_m \right] + \ldots$$

With this reordering of terms the number of Fourier to spherical harmonic Legendre transforms required for the temperature equation is reduced from three to two. The same device can be used in the moisture equation.

Temperton (1991) has suggested a very useful halving of the transform requirement in the vorticity and divergence equations from four to two multilevel Legendre type transforms. Temperton's technique involves taking the recurrence on \( P_{l+1}^m, P_{l-1}^m \) for \( \cos \phi \frac{\partial}{\partial \phi} \left( \sin \phi \right) \) outside the Gaussian integration to give a recurrence for the spherical harmonic coefficients of \( A/\cos^2 \phi, B/\cos^2 \phi \) which appear in both evolution equations.

Note that writing the evolution equations in advective form instead of flux form would yield a much simpler form for the grid to spectral operations for the spectral tendency evaluations; however, this is at the expense of requiring additional transforms to grid space of the spatial derivative terms which appear in the non-linear terms. For example, for the advective form of the temperature equation, \( \partial T/\partial \lambda, \cos \phi \partial T/\partial \phi \) are required in addition to the \( T \) field itself; i.e. three spectral-grid transforms and one grid-spectral transform. In flux form the temperature equation requires one spectral-grid transform (\( T \)) and two grid-spectral transforms.

**Multitasking**

In the single-processor version of the model considerable effort had been put into vectorising the associated Legendre transform algorithms. With rhomboidal truncation these algorithms focused on the use of square arrays and achieved considerable efficiency by vectorising over one of the spectral wave numbers \( l \) or \( m \).

The model transforms involve loops over latitudes, fields, levels and two spectral wave numbers. The natural variable for multitasking of the model dynamics and physics calculations is latitude, as all the calculations in grid-point space can be performed on a single latitude of data at a time. In the context of multitasking over latitude the grid to spectral transform algorithms required multiple copies (at least one per processor) of the spectral coefficient arrays which are updated during the accumulation of contributions from all latitudes to the Gaussian quadrature with a final summation of the separate copies outside the latitude loop.* Furthermore, if the order of assignment of latitudes to processors changes due to run time load effects the results will still not be identically reproducible (even though there is no

*In the initial multitasked implementation of the BMRC model by Tony Meats at Cray Research.
reason to expect the differences to be computationally significant). To economise in terms of memory usage it was chosen to multitask this step over Fourier wave number \( m \) using multiple copies of the intermediate Fourier coefficient arrays.

For the spectral transforms in both directions vectorisation is over the innermost loop consisting of a stack of real and imaginary variables for all levels and multiple fields.* In a 19-level model, for example, this typically yields a vector length of at least \( 2 \times 2 \times 19 \) as two fields at a minimum are handled together. An advantage of this strategy is that it leaves the two spectral wave numbers as having no effect on the vectorising of the Legendre transforms. Accordingly, it is thus relatively straightforward to change the spectral truncation from rhomboidal to triangular, say, without impacting on key algorithmic efficiencies.

The present level of the multitasking is such that the forecast model runs 2.44 times as fast on three processors as on a single processor on the Bureau’s three-processor CRAY Y-MP.

*As recommended by David Dent of ECMWF.