

History of NWP in Australia – 1970 to the Present

William Bourke
*Bureau of Meteorology Research Centre
Melbourne, Victoria, Australia*

Introduction

From 1970 until the present, the research and development of NWP in Australia for operational application has been primarily associated with

- (a) research and development of the Joint CSIRO/Bureau of Meteorology entities of the Commonwealth Meteorology Research Centre (CMRC, 1969 – 1974), and the Australian Numerical Meteorology Research Centre (ANMRC 1975- 1984) and of the Bureau of Meteorology Research Centre (BMRC, 1985 – present); and from
- (b) the operational application and use of the NWP by the BoM during that time.

The account of this work represents a personal view of this history reflecting my observations and participation from the inception of CMRC in April 1969 until the present time in BMRC. Having been closely involved in spectral modelling I am also adding some comments on aspects of this component of NWP in its earliest years.

When contemplating the course of these events over the past 35 years what appears to be very remarkable is the significant coherence and continuity in both the aspirations of key researchers in NWP research and in the application of NWP in BoM operations over this 35 year period; this is the prime focus of this paper .

Much of the relevant early organizational history of NWP research is recounted in the CMRC/ANMRC Valedictory Report (1984; subsequently denoted as VR84) and further described by Gardner (1993). With the formation of BMRC in 1985 the BoM assumed “primary responsibility for research in support of its own operations and services” which included the full responsibility for NWP; the BoM Annual Reports since 1985 describe the role of BMRC in the Bureau.

The arrangements for NWP in the Australian context over the years 1969 – 1984 were marked by major inter organizational difficulties between the BoM and CSIRO in relation to the CSIRO/BoM Joint Centres. During the ensuing 20 years, a legacy of earlier times has been that useful cooperation in atmospheric modelling for NWP and Climate Modelling between BMRC and CSIRO has been minimal although during this time the demands in these scientific areas have become increasingly more complex. Recent endeavours to develop relevant collaboration and to establish more than sub-critically sized research capabilities are somewhat overdue.

So much for the organizational perspective ; the journey of NWP over the past 35 years in Australia has been one of scientific innovation and effective operational implementation that has contributed to ever improving operational prediction . NWP has been practised elsewhere in Australia during these past 35 years but this account is primarily limited to that associated with research and its implementation in operational NWP as conducted by the BoM. I propose to present this narrative in the obvious chronological order. I have referenced in the most part CMRC/ANMRC Annual reports (1970 – 1978) and Quarterly Reports (1974-1985) , the annual Research in BMRC reports from 1985- 2003 and BMRC Research Work reports (1985 – 1996), the Operations Bulletins of NMOC as well as the published literature in preparing the following. Relevant review of (a) meteorological analysis for the Australian region and for the southern hemisphere has been given by Seaman (1997) and of (b) limited area NWP for the Australian region has been given by Leslie and Dietachmayer (1992). The

comprehensive account of Seaman (1997) highlights the particular difficulties faced in the southern hemisphere in developing methods of objective analysis in the early years.

Background to the Seventies

The earliest efforts of NWP in Australia included the pioneering calculations of the late Ross Maine (1957) using a one dimensional advection model, an integration of an equivalent barotropic model for the Australian region conducted at Melbourne University by Radok and Janssen (1959) and the work of Maine (1966) on numerical analysis for the Australian region in an M.Sc. thesis also at Melbourne University. The work of Maine and Seaman (1967) at the Bureau of Meteorology in developing an operational analysis system for the Australian region provided the foundations for ensuing research and development in objective analysis for the region, and the southern hemisphere. At the same time Maine (1967) had developed a quasi-geostrophic barotropic model for the Australian region which became the first operational NWP system in the Bureau in 1969. [An extensive recent account of “Early Operational NWP outside the USA”, from the early fifties until the late sixties, describing international developments in NWP has been recently prepared by Persson (2004); he describes developments in 18 countries outside the USA including those in Australia and chronicles the evolution of the developments in NWP from the earliest calculations by Charney et al (1950).] A possibly not so well known milestone in Australian NWP is the first primitive equations prediction for the southern hemisphere carried out by Reg Clarke at the Princeton Geophysical Fluid Dynamics Laboratory (GFDL) in 1966 utilising digitised manual analyses of the southern hemisphere (March 1-5, 1965) to initialise and verify the then GFDL N30 9 level model; these 5 days of manual analyses incorporating use of TIROS 9 cloud imagery in attempting to deal with the massive data void issues, required months of work to generate; the work is described by Clarke and Strickler (1972) and they cited encouraging forecasts particularly for day two in the Australian region.

The rationale for a real effort and resource commitment to NWP Australia by Government in the late 1960s arose from the recognition by that “the ultimate production of operational models for the southern hemisphere or any substantial part of it would demand a scale of effort, a massive component of developmental as well as research work, a computer strength and a number of supporting staff, which only the Government would be able to provide”(Gibbs and Priestley (VR84) . The support of Priestley reflected his close involvement in the Joint Organizing Committee (JOC) for the Global Atmospheric Research program (GARP) which was established in 1967; Smagorinsky, a fellow JOC member visiting Australia at that time in a Guest of Honour broadcast (December 1967 on the ABC) when describing possibilities for electronic computers in atmospheric modelling highlighted the role that Australia could play describing the GARP program as “ a glorious opportunity for Australia”.

The requisite computer strength had become available in the establishment in Melbourne of one of three World Meteorological Centres and the associated installation in 1967/8 of the truly state-of-the-art dual IBM 360/65 computers; the requisite research staff were provided through new positions within the Public Service for the Bureau and new positions from CSIRO. The initial annual cost of setting up CMRC was estimated in 1969 to not exceed \$50,000 with an annual cost of \$300,000 finally when the Centre achieved its immediate staffing target of 33 scientific and technical staff.

The Seventies

When CMRC was formed in April 1969, the numerical systems locally available were an Australian regional multi-level analysis scheme and an Australian region single level barotropic prediction model. Major efforts in support of operations in 1970/1971 focussed on extending and refining the multi-level analysis system including the capability of 12 hour analysis cycling of predicted mean sea-level-pressure and 1000-500 hPa thickness as first

guess data to the subsequent analysis; the analysis domain was also extended to the hemisphere at this time. A significant component of the robustness of these initial analysis systems came from the incorporation of cloud satellite imagery interpretation where manual analyses of sea-level pressure and 1000-500 hPa thickness were prepared and digitised taking into account all available conventional data and imagery. (The basis for these manual interpretative procedures is presented in the legendary Technical Report by Guymer (1977)). The digitising consisted of extracting point values on a fixed grid from the manual analyses, which became known as PAOBS (paid observations), and then passing these to the numerical analysis where they are treated as observations. The history and use of sea-level PAOBS is to be described later in this meeting by R. Seaman; the use of 1000-500 hPa manually derived data known as THKLs had a lifetime somewhat beyond what was warranted in view of the generally robust coverage and availability of satellite soundings e.g VTPR from 1972 onwards; but they were only eventually phased out in the early 1990s in GASP and in the mid 1990s in LAPS .

Multi-level analysis systems for the southern hemisphere with significant refinements to the regional multi-level analysis system were introduced in 1970/71. The basis for these analysis systems using univariate Cressman (1959) analysis algorithms were presented by Maine (1966) and Maine and Seaman (1967); filtered baroclinic models based on Maine (1972) and Noar and Young(1972) were implemented operationally for the region in July 1970 and for the hemisphere in 1971.

A major research effort at this time was the development of a 6 level primitive equations model suitable for extended range (1- 4 days) operational forecasting for the southern hemisphere. This work derived from close collaboration between the BoM and GFDL in Princeton and is described by Gauntlett and Hincksman (1971). Doug Gauntlett had visited both the National Meteorological Centre in Washington and GFDL in Princeton in 1969 to assess the possibilities of the then available primitive equation models. The 9 level (N30) hemispheric general circulation model developed at GFDL by Smagorinsky et al (1965) was identified as the most suitable model on which to base the development of a NWP system for the southern hemisphere following these assessments. The GFDL model as implemented in CMRC became known locally as the PE (primitive equations) model. Although producing superior predictions for the southern hemisphere in comparison to the filtered baroclinic model the PE model required approximately 4 times longer to execute (requiring 90 minutes per model day). The lower computational demands of the filtered model were decisive in it being chosen for operations for the hemisphere; it remained in operations for the hemisphere until January 1976; the regional baroclinic model remained in operations until 1977.

Although not adopted by the BoM for operational use, the PE model was the vehicle for extensive research and development of the earliest analysis-prognosis system for the hemisphere. [In addition it was the basis for pioneering General Circulation simulations in which the full set of available physics was implemented, see Anderson and Noar (1974); in the NWP mode some physics was not implemented e.g full radiative transfer] . An operational trial of a 12 hour analysis/prognosis system for the southern hemisphere using the PE model was evaluated in June/July 1971 and demonstrated superior performance to the then higher resolution regional filtered baroclinic model in the Australian region. (Gauntlett et al, 1972).

While huge effort and resources were being devoted to provision of substantial operational capability in NWP to the Bureau, other activities were being explored. Having arrived from a nuclear physics background I was familiar with particle scattering theory and the mathematics of angular momentum coupling in low energy reactions; indeed what I knew as Clebsch-Gordan coefficients masqueraded in the meteorological literature as interaction coefficients which were encountered in the dynamical equations once the non-linear terms were expressed in terms of spectral expansions of spherical harmonics. This appeared as an oasis to a novice

amidst the plethora of finite difference schemes that abounded at the time in an attempt to solve pressing problems with converging meridians, with interhemispheric flow, with non-linear instability among others. Accordingly I formulated a shallow water model in spectral form based on vorticity and divergence equations and implemented this on the BoM computer; subsequently on an extended visit to Montreal in 1970/71 I incorporated a two dimensional transform within this framework (Bourke, 1972) having obtained access to papers by Orszag (1970) and a report by Eliassen et al (1970) which presented details of the transform method. Orszag formulated the transform method in terms of a full two-dimensional transform for the vorticity equation i.e incorporating Legendre and Fourier transforms; Eliassen et al initially used only a Legendre transform and in subsequent work Machenhauer and Rasmussen (1972) demonstrated the application of the two dimensional transform for the shallow water model (using momentum prognostics). The comparison of the interaction coefficient formulation and the transform approach in Bourke(1972) demonstrated among other things the efficiency gains available in spectral models based on the transform approach.¹ Bourke (1974) subsequently extended the transform method to a multi-level primitive equations semi-implicit global spectral model with a finite difference representation in the vertical.²

While early demonstrations of the transform spectral technique were compelling there remained some unresolved queries. Weigle (Ph. D. Thesis Univ Michigan 1972) had shown that the truncated shallow water equations did not formally conserve energy, and the same issue clearly translated to the baroclinic spectral model. There was also some doubt about the ability to represent topography spectrally whilst maintaining stable integrations. Additionally questions as to what transform grid resolution would be required to represent physical processes adequately was not obvious. Integrations within CMRC of the multi-level spectral model validated that these issues could be adequately managed.

In January 1976 the CMRC hemispheric spectral model was implemented operationally in the Bureau with 7 levels at rhomboidal truncation of wave number 15 and became known as SPECPROG. Operational trials had demonstrated its superiority to the then 6 level filtered baroclinic model (N30) in regional and hemispheric prediction to 48 hours. The spectral model as implemented operationally incorporated a double transform loop to handle the non-linear physical processes in the PBL and convection and these were implemented by Kamal Puri. (This model required 40K words of memory and employed a spectacular overlay structure developed by Robert Thurling the key IT contributor to the model coding development). The physical parameterisations subsequently were extended to include the Manabe/Lacis/Hansen radiation codes by Bryant McAvaney in a nine level version of the

¹ The history of NWP to the extent that this involves spectral models should include reference to the Stanstead seminar held in Montreal in July 1971. From some points of view this meeting corresponds to t=0 for many subsequent transform spectral modelling endeavours. A memorable aspect of the meeting was an evening debate on the resolution “ that spectral methods of integrating the dynamical equations will replace the grid point method in most operational and research applications in the near future”. The humorous transcript of the debate is included in the proceedings ‘ Proceedings of the ninth Stanstead seminar July 1971, McGill University, Montreal Publication in Meteorology No. 103’. – the resolution was lost narrowly – although suggestion was this would have been different if “will replace” was changed to “should replace”.

Versions of the CMRC shallow water spectral transform model were requested by and provided in 1971 to A.Robert(Canada), C. T. Gordon (GFDL) and B. Hoskins (U.K)

A version of the CMRC adiabatic multilevel spectral model was requested and provided to Andre Robert (Canada) in 1972.

² In going through some old correspondence files I was reminded of the encouragement Andre Robert gave to Miyakoda and Smagorinsky at GFDL in late 1971 , in urging GFDL to consider the transform spectral model as the basis for future global modelling.

model. This model was used in the first demonstration of the transform spectral method for global general circulation.(McAvaney et al ., 1977). Further upgrades to the physics of the model were implemented with the inclusion of the Fels-Schwarzkopf radiation and stability dependent boundary layer schemes developed at GFDL during an extended visit I made to GFDL in 1977. As in earlier times with the PE grid-point model the continued support of GFDL ,this time through Kiku Miyakoda and Joe Sirutis with our model development, was very forthcoming and is still evident in the present operational global NWP codes which derive from those earlier 1977 developments.³

As part of a concerted effort to improve prognoses in the Australian region the hemispheric PE model was converted to a limited area model. A CMRC policy decision was taken in 1974 to commit to the spectral model for the large scale and to the PE model for the limited area regional scale . A major development of the PE model was the inclusion of semi-implicit time stepping (Gauntlett, 1974) which was a non-trivial development given that the model advective equations were cast in the flux form. The PE model formulation underwent a number of upgrades and consolidations as described by Gauntlett et al (1978) and McGregor et al (1978); the latter paper retaining the flux form of the dynamic equations but introducing the use of a staggered grid. The PE model replaced the filtered baroclinic model in regional NWP operations in September 1977 at a resolution of 250 km with 6 levels and was known as ARPE.

As mentioned already a distinguishing feature of the early NWP in the southern hemisphere relative to the northern hemisphere was the sparseness of the observational data base. Accordingly innovative refinements to the objective analysis methods were particularly relevant and a series of significant developments were introduced by Seaman (1972, 1976) and by Seaman et al (1977). This latter paper details a variational strategy for blending geopotential height, wind analyses and manual interpretation of satellite imagery; a two dimensional blending scheme was implemented for regional operations in 1975 with the three dimensional blending extension implemented operationally in December 1976.

From 1972 onwards extensive work on processing satellite data had been conducted by Graeme Kelly focussing on strategies to use the VTPR clear column radiances from the National Oceanic and Atmospheric Administration Satellites (NOAA-2,3 and 4). In December 1974 Kelly had begun developing an analysis/prognosis cycling system using the spectral model to evaluate the use of VTPR retrievals replacing the use of THKLs as then presently used in operations. In 1976 Kelly demonstrated very successfully that VTPR data combined with MSL PAOBS was adequate to maintain for over one month a warm running 12 hour analysis/prognosis system for southern hemisphere prediction which was comparable if not superior to the then operational practice.

Kelly, Mills and Smith in 1976 presented a particularly significant and pioneering demonstration of the relevance of satellite soundings in the Australian region . (Kelly et al 1978). William Smith while on an extended visit to ANMRC and CSIRO was able to provide tapes of Nimbus-6 retrievals and radiances; Nimbu-6 carried the IR and microwave instruments which were close predecessors of the TIROS-N instruments. In a series of ARPE assimilation experiments Kelly et al were able to show clear positive impact from the use of the sounding data for the Australian region 24 hour prediction.⁴ These experiments were

³ A version of the this ANMRC general circulation model was made available at NCAR during an extended visit by Kamal Puri in 1978 and it formed the start of the NCAR CCM series of models. Subsequently versions of the ANMRC GCM were made available in the 1980s to Melbourne University and also to CSIRO Atmospheric Physics.

⁴ The ANMRC ARPE analysis/prognosis system model was subsequently adopted at University of Wisconsin for high resolution assimilation experiments using TIROS-N soundings over North America.

particularly significant at that time in view of the controversies surrounding some experiments associated with Data Systems Tests (DST) for the First GARP Global Experiment (FGGE) and the difficulties northern hemisphere centres were having in demonstrating positive impact in their NWP suites with satellite data. These experiments impacted on Bureau planning and implementation of local read-out⁵ of the TIROS-N sounders to support rapid access to soundings for timely use in ARPE, and recognised Kelly's work in developing improved real-time retrievals from VTPR using discriminant regression analysis methods. Overall these studies gave particular impetus to the ANMRC's effort on assimilation systems particularly focussed on the advances in observational coverage in the southern hemisphere during the 1979 FGGE program.

In the late 1970s serious doubts were expressed by senior management of the Bureau as to the usefulness of the effort in NWP, not to mention the whole rationale for the existence of ANMRC which was being challenged at the highest levels by the Bureau and by CSIRO Atmospheric Physics. ANMRC was involved directly in or caught up in numerous reviews at this time; the short version is that the subsequent decisions to close ANMRC could be seen as evolving from these machinations.⁶

Early Eighties, post FGGE and the end of ANMRC

The work of the previous decade established the framework for significant experimental NWP research in the 1980s. Almost all of the recent research had been conducted on CSIRO CDC 7600 computers in Canberra; the original BoM IBM 360/65 computers remarkably remained in operations until 1981. The BoM acquired new Facom M200 computers in 1981 and this greatly helped experimental progress although the purchase of this scalar machine at a time when Cray Vector machines were already established at other major international centres left the Australian NWP community with limited operational capabilities in the coming decade. In the last year of ANMRC, access to CSIRO's new CYBER 205 supercomputer was available and expansion of model resolutions for experimental regional and the hemispheric systems became possible. Access to adequate computing was a recurring issue in the 1970s and 1980s and was not really resolved until the BoM acquired its own supercomputers in 1989; the full narrative on this would be exceedingly long.

With the advent of FGGE considerable effort was put into experimenting with the new data sources available; in particular up to 300 drifting buoys provided for the first time a substantial representation of sea-level pressure and the improved HIRS and MSU sounders on TIROS-N provided higher resolution and quality radiances and soundings. A new assimilation system had been developed in the late seventies within the framework of the hemispheric spectral model at a resolution of R21 with 9 levels incorporating in the Gaussian /sigma co-ordinates of the model 6 hourly direct analysis of increments to model first guess. A decisive component of this scheme was the use of and refinement of non-linear normal mode initialisation implemented by Kamal Puri following his work with Akira Kasahara in 1978 at NCAR (Puri 1981, 1982). Impact studies for the hemisphere showed clearly the gains available from the new FGGE data base and also validated the new assimilation strategies for the hemispheric system. (Bourke et al, 1982). This system was provided for operational use in 1984 and became operational in March 1985 providing 48 hour prediction twice daily and became known as HASP. Work on univariate statistical interpolation (SI) had also been undertaken by Seaman 1984; a univariate SI was implemented within the spectral model

5 In early 1981 the BoM routinely commenced local read-out of TOVS receiving two to three orbits per day over eastern Australia at 60 km resolution with temperature profiles available within 2 hours of overpass.

6 Gardiner (1993) and more recently Seaman (2005) provide comment on these matters with views in contrast to explanations which were part of the Valedictory Report (VR84).

assimilation system in this operational upgrade in March 1985. Experiments at this time also indicated that THKLs could be safely removed from operations in the hemispheric system when full VTPR coverage was present.

The limitations of NWP performance in the Australian tropical latitudes prompted a new initiative on tropical analysis with the development of an objective analysis system which became routinely available (twice per day) from July 1983 and was managed as its successors are today by the Darwin RMC.(Davidson and McAvaney 1981).

An upgraded research version of the ARPE model was developed in 1983/1984 utilising 10 levels and 150 km resolution with revised physical parameterisations and capability for telescoping or nesting to fine mesh versions of the model. The model continued to use the Variational Blending Analysis scheme of Seaman et al (1977) and also incorporated the vertical mode initialisation scheme of Bourke and McGregor (1983).

In 1984 Puri commenced work on diabatic initialisation using GMS satellite sensed cloud top temperatures to specify heating profiles and thereby initialise divergence in tropical regimes. At this time research was commenced by Kelly on developing physical retrievals of locally received radiances.

Bureau of Meteorology Research Centre (BMRC) and the Late Eighties

The BMRC was formed in January 1985 and commenced with a staff complement of 35 positions with a target level of 64 positions. Research staff from ANMRC and from the Bureau's own Research and Development Branch formed the core of the new centre's activities in NWP. A priority research activity of BMRC, identified at the outset, was the continued development of short-range and medium range numerical weather prediction.

Access to the remotely located CSIRO CYBER 205 continued as a high priority requirement in the continued development of the NWP suite in research. The limitations of the available computer capacity are highlighted in the accompanying table where a factor of 10 in performance difference shows in options available then.⁷ While useful NWP research was feasible on the Cyber 205 significant operational upgrades in the first five years of BMRC were highly constrained; it is worth recalling that ECMWF was utilising T63 global systems operationally in 1982.

A new version of the regional NWP model, known as FINEST was introduced into operations in August 1986 with 12 levels and a horizontal resolution of 150 km; this system continued to use the Seaman et al (1977) 3D variational blending analysis system. A more substantial refinement of the regional system was also being developed utilising 6 hour cycling, the univariate statistical interpolation scheme developed by Seaman and the vertical mode initialisation scheme of Bourke and McGregor (1983). This system which became known as RASP utilised finally 15 levels in the model and 11 levels in the analysis at 150 km resolution and became operational in October 1989 producing 36 hour predictions twice per day; the new analysis system reflected the most sophisticated used hitherto in the BoM combining univariate statistical interpolation with variational mass-wind blending and interpolation of analysis increments rather than full fields (Mills and Seaman 1990). NESDIS produced 'satem' retrievals at 500 km resolution and JMA cloud drift winds were used in this system.

⁷ Computer Timings in Minutes for Hemispheric and Global Assimilation/Prediction

	1 Day Prediction			1 Day Assimilation				
NWP System	H21	G21	H31	G31	H21	G21	H31	G31
Facom M200	14	27	60	120	29	100	90	300
Cyber 205		3		11		20		60

The new analysis scheme was developed to be independent of map domain and projection and was thus able to support large scale as well as regional analysis. This domain independence strategy has been maintained and indeed extended in the most recent analysis systems being now implemented and developed in BMRC. The RASP system was upgraded in May 1994 to have a horizontal resolution of 75 km , with 12 levels for the analysis and 17 levels for the model.

The University of Wisconsin McIDAS Data Access and Display systems was installed in the BoM in 1985 on a FACOM M180 computer to facilitate improved satellite data processing. During 1986 GMS-3 imagery, real-time observational data, and numerical analyses and prognoses for the Australian region became accessible in the McIDAS system; additionally Wisconsin cloud drift wind software was installed within McIDAS and the initial assessment of these products for operational usage commenced. The operational use of the locally produced cloud-drift winds in the RASP system was implemented in June 1992. (Le Marshall et al., 1993).

In 1987 physical retrievals of temperature from the TOVS radiances obtained in local read-out from Melbourne and Perth were developed and implemented within the McIDAS processing.(Le Marshall et al 1989). Extensive experiments continued in the early 1990s to optimise the use of remotely sensed data beyond the straightforward use of retrieved temperatures known as ‘satems’ which were provided over the GTS by NESDIS typically at a horizontal resolution of 500 km. The use of locally derived TOVS retrievals in the RASP system became operational in October, 1993. (Le Marshall et al., 1994).

The major field experiment AMEX conducted by the Bureau in collaboration with Monash University in Jan/Feb of 1987 provided a major focus for research and development in tropical NWP. The Davidson and McAvaney (1982) tropical analysis system was employed to provide real-time 6 hourly tropical analysis for this period. The AMEX observational program and BMRC tropical analyses thus provided a significant step in the development and validation of tropical NWP (Davidson and Puri, 1992a). A tropical prediction model capability had been under development since 1985 from an extension of the ARPE model to run on a mercator projection for the 40S to 45 N, 70E to 180E domain with horizontal resolution of 250 km and with 6 levels. (Puri et al. 1992). Additional developments to the tropical analysis system included a new form of bogus data namely estimating tropospheric moisture profiles from the GMS IR imagery (Mills and Davidson, 1987), the use of GMS based estimates of rainfall rates using regressions on the Japanese geostationary meteorological Satellite (GMS) cloud-top temperatures. (Puri and Davidson, 1992.) and the use of tropical cyclone bogussing (Davidson and Puri , 1992b). Studies of tropical prediction became effective and possible over a range of resolutions including assessments of tropical cyclone prediction at 100 km resolution including for example the well observed tropical cyclones occurring during the AMEX (Jason and Irma). The global spectral model physical parameterizations were incorporated in the Tropical model in 1989 with the resolution upgraded to 150 km with 9 levels, replacing the earlier ARPE based parameterisations; this was the first attempt to unify the physics packages in use in the centre across the range of models and paved the way for the current strategies. This tropical analysis/prediction system subsequently became operational in 1992 with 15 levels in the analysis, 19 model levels and at a horizontal resolution of 100 km.

A frequent activity in assessing NWP performance has been comprehensive case studies and diagnostics of the dynamics of significant weather events throughout these years of NWP development; notable among these by way of example is the study by Mills and Russell (1992) in examining the Eastern Australian floods in April 1990. This particular study highlighted the potential for higher resolution prediction but also provided insight into improved diagnostics that could aid the forecasters in interpreting NWP output.

Experimental hemispheric assimilation at 9 levels but at R31 resolution were extensively studied with access to the CYBER 205 in 1987/1988. ⁸ Global assimilation and prediction to 5 days at R31/L9 commenced quasi-operationally in July 1989 on the BoM's own ETA10 supercomputer acquired in late 1988; this system became known as GASP. The upgrade to global from the hemispheric domain and increase in resolution showed marked improvement over the previous system and also resolved the long standing cold bias in the low-latitudes/tropics of the southern hemisphere; this was shown to be due to the almost complete absence of the ITCZ in the southern hemisphere with the hemispheric model truncation – this problem was not so acutely apparent in similar studies of hemispheric truncation for northern hemispheric models. At this time global general circulation studies were conducted with the global spectral model at R21/L9 and R31/L9 with useful enhancements and validations of the physical parameterizations including shallow convection in the model. (Hart et al 1990).

A major software development project in support of NWP and general circulation modelling was the adoption of the NCAR modular processor (Naughton and Balgovind, 1990) for post-processing, diagnosis of, and display of model output. This system has been the major package for processing of global model fields in research and operations up until the present and much of the NWP display in current operations still depends on this system.

In August 1990, the Bureau's ETA10P was replaced by a Cray-XMP; a somewhat unexpected event associated with the damaging of an upgraded ETA just prior to its delivery, the demise of CDC in the supercomputer market, and negotiations which saw the contract with CDC amended to provide for the replacement of the ETA10P with a Cray X-MP installation.

An important visit to BMRC was made by Michael Tiedtke of ECMWF for 3 months from December 1990; during this visit Michael collaborated with Kamal Puri on implementing a version of the ECMWF mass-flux convective parameterisation (Tiedtke 1989) in the GASP model. This development was to be later incorporated into the operational GASP and LAPS prediction systems.

A major project in the early 1990s was a multivariate analysis system developed initially within the framework of the sigma co-ordinates/Gaussian grid of the global spectral model. The GASP system was updated in December 1992 to R31/L19 incorporating the multivariate statistical interpolation, (analysing thickness rather than temperature) and using 250 km resolution TOVS obtained directly from Washington rather than over the GTS. In the global assimilation significant positive impact was obtained from this increased resolution of the satellite data. The model physics now included diagnostic cloud and gravity wave drag parameterisations. GASP was further upgraded to R53/L19 in March 95 with prediction extended then to 7 days (Bourke et al., 1995; Seaman et al., 1995), and then upgraded again to T79/L19 in December 1995; the 1995 upgrades included non-linear incremental normal mode initialisation in the assimilation, and in the model included the Tiedtke(1989) mass-flux convection with the model transform grids incorporating the thinned grids. (Courtier and Naughton 1994). The inclusion in the multi-variate analysis system of a data cross-validation scheme provided a very effective means of quality control and also data monitoring within the assimilation system and bias detection of the regional synop network. (Seaman, 1994, 1999).

A regional NWP project of significance undertaken in 1990 was the redesign of the numerics of the limited area prediction model, formulated on a non-staggered (Arakawa A) including 3rd order upwinding (Leslie and Skinner, 1994) using a split-explicit time integration approach. One rationale for the choice of an explicit approach was the relative simplicity of

⁸ These tests over 4 months used a complex but automatic set of jobs communicating between Bureau Facoms and CSIRO FACOMS, a CDC front-end and the CYBER 205 over a very modest bandwidth link to Canberra; a tribute to Gerry Embery's IT skills and perseverance.

coding and achieving long vectors which was of particular advantage on the ETA10P. Subsequently a total redesign of the system incorporated a flexible use of a latitude longitude grid with nesting capabilities and algorithm modifications to avoid 'A' grid solution decoupling. The then physical parameterisations in use in the GASP system were also implemented in the model. The analysis, updated to use the multi-variate analysis algorithms developed within the GASP framework, was now implemented in sigma co-ordinates with horizontal resolution of 75 km and 19 levels now applied for both the analysis and model. A new initialisation scheme was introduced namely the digital filter (Lynch, 1993), replacing the vertical mode scheme. This new regional system known as LAPS was implemented operationally in July 1996. (Puri et al., 1998) and upgraded in September 2002 including an extension of the forecast range from 48 to 72 hours.

The major upgrade in BoM supercomputing with the establishment of the Joint BoM/CSIRO HPCCC and the installation of the NEC SX-4 in August 1997 and the install of the dual SX-5 systems in 1999 and 2001 has provided in the most recent years a much increased computing capacity. It has thus been possible to substantially upgrade the major NWP systems in recent years and to make such upgrades somewhat more frequently. The most recent BoM upgrade within the HPCCC to include a 23 node SX-6 facility now affords scope for very significant developments of our NWP capabilities.

The success of the LAPS system has allowed a unified approach to regional assimilation and modelling for the tropical domain and at higher resolution for both the region and in the tropics. With the greater computing capacity since late 1997 it has been possible to increase the resolution of the LAPS system for both analysis and prognosis to 37.5 km in the horizontal with 29 levels (July 1999). A 12.5 km resolution version of the model, known as Meso-LAPS had become operational in May 1977 for the two domains south-east and south-west Australia but it was possible to replace this in November 1999 with a system at 12.5 km resolution with 29 levels applied over the entire Australian domain for prediction to 36 hours. The Meso-Laps model prediction system was also implemented at a resolution of 5 km in operational support of the Sydney Olympics; this 5 km version of the model is also currently operational for Melbourne, Sydney and Brisbane regions.

Paralleling these regional applications of the LAPS system has been the development of: (a) a tropical region analysis/prognosis system (TLAPS) with a resolution of 75 km and with 19 levels implemented in June 1977 upgraded to 37.5 km in September 1999 and further upgraded in January 2003 including extension of prediction from 48 to 72 hours and (b) a tropical analysis/prognosis system (TCLAPS) comprising large scale analysis /prognosis operating at a horizontal resolution of 75 km and with 19 vertical levels containing a nested 15 km resolution model to support tropical cyclone prediction. (Davidson and Weber, 2000). TCLAPS is initiated upon the identification of any named tropical cyclone and employs a sophisticated tropical cyclone bogus insertion procedure. The large scale analysis of TLAPS and TCLAPS utilise in addition to the multivariate statistical interpolation the GMS based synthetic moisture profiles and the GMS based estimates of convective heating in a nudging strategy. TCLAPS became operational in December 1999.

The GASP analysis and prognosis system was upgraded in December 1998 to a substantially increased resolution of T239/L29, incorporating semi-Lagrangian time stepping. Model predictions were extended to 8 days; global estimates of predicted GMS satellite brightness temperatures were also available as developed by Rikus (1997). The assimilation component was enhanced with the operational implementation of 1D VAR radiance assimilation for NOAA14 (TOVS) and NOAA15 (ATOVS) in August 2000; this use of radiances replaced the use of NESDIS based retrievals which had been used for the past 20 years in one form or another. An important aspect of the 1D VAR treatment of radiance has been the use of the bias correction scheme developed by Harris and Kelly (2001). NOAA16(ATOVS) were additionally assimilated as of June 2001, and NOAA17 as of Jan 2003.

The GASP based 1D VAR was also implemented in the LAPS suite as of September 2002 replacing the use of NESDIS retrievals which had been used in the LAPS suite for the previous 3 years; the use of local read-out radiances in the LAPS suite has been inoperative since 2000 with the system not being upgraded to support the ATOVS instruments. A high priority at present is to re-instate the local read-out radiances to avoid the current loss of late orbits over the western half of the Australian region systems.

The overall BMRC analysis capacity has been substantially enhanced with the development of the generalized multi-variate statistical interpolation scheme (GenSI) This system is designed to support a unified analysis system for both the regional and global domains, is implemented in observations space and supports comprehensive radiance assimilations. The GenSI was implemented operationally in GASP in May 2004 and is scheduled to be used in the suite of LAPS systems in the near future.

Ensemble prediction systems have become increasingly valued within the NWP community in the past decade and in 1997 a prototype ensemble system development was commenced for the GASP system. This has followed the strategy of using singular vectors, as pioneered at the ECMWF. A T119/L19 based system with 33 member prediction to 10 days in the ensemble became operational in Nov 2004. (Bourke et al, 2004) after extended operational trials.

The history sketched above has of necessity omitted many aspects of the developments over the past 30 years . Of particular note in most recent years is the substantial effort expended on improving the key physical parameterizations used in the range of models, but equally importantly is the effort concentrated on developing a unified physics package to support the global and regional modelling systems. The most recent implementations of GASP and LAPS (and the global climate model) have benefited from this work as they now all use what is referred to as the BAM model physics. Equally importantly has been the unification of the analysis systems through the development of GenSI. The BoM's acquisition of the very effective HPC configurations in the past 7 years has greatly enlarged the research and operational capabilities in NWP; the associated supporting IT infrastructure and data management have similarly been central to effective progress in NWP. A number of the following presentations will expand more fully on these topics in this examination of the past, present and future of numerical modelling.

As a final comment it is appropriate to record that in the face of all this work over all these years the NWP suites available in Australia for operational use in the BoM are not as effective as several of the more comprehensive systems available internationally. The scientific personnel to capitalise on the now available satellite based observations and on the knowledge of the key physical processes that need to be represented in the models have simply not been available here. In view however of my earlier comments on the closure of ANMRC I think it is also appropriate to suggest that the complexity of the current tasks confronting modern NWP would have rapidly outstripped the capabilities and indeed vision of the earlier Joint centre ANMRC. It is to the BoM's credit that we have made the progress described in the above especially within the past 20 years and that much of the necessary infrastructure needed to support what would seem obviously core business of a national weather service has been forthcoming. A valid concern is that the investment may be dissipated if sufficient scientific staff resources are not available to support the core activities that modern NWP now requires.

References

- Anderson, D.L.T and Noar, P.F. 1974. The synoptic verisimilitude of a mid-latitude cyclone generated in a southern hemisphere general circulation model. *Mon. Wea. Rev.* 102, 613-629.
- Bourke, W.P. 1972 An efficient one-level primitive equation spectral model. *Mon. Wea Rev*, 100, 683-689.
- Bourke, W.P. 1974 A multi-level spectral model: I Formulation and hemispheric integrations. *Mon. Wea. Rev.*, 102, 687-701.
- Bourke, W.P., Puri, K.K, Seaman R., McAvaney B. and LeMarshall J. 1982 ANMRC data assimilation for the Southern Hemisphere. *Mon. Wea. Rev.*, 110, 1749-1771.
- Bourke, W. P., Puri K.K., and Seaman R. 1982 Numerical weather prediction studies from the FGGE Southern Hemisphere data base. *Mon. Wea. Rev.*, 110, 1787-1800.
- Bourke, W.P. and McGregor J.L. 1983 A Nonlinear Vertical Mode Initialization Scheme for a Limited Area Prediction Model. *Mon. Wea. Rev.*, 111, 2285-2297.
- Bourke, W., Hart, T.L., Steinle, P., Seaman, R. S., Embery, G., Naughton, M. and Rikus, L. J.1995: Evolution of the Bureau of Meteorology's Global Assimilation and Prediction system. Part 2: resolution enhancements and case studies. *Aust. Met. Mag.*, 44, 19-40.
- Bourke, W., Buizza, R, and Naughton, M.J. 2004. Performance of the ECMWF and the BoM Ensemble Prediction Systems in the Southern Hemisphere. *Mon. Wea. Rev.*, 132, 2338–2357.
- Charney , J.G., Fjortoft, R. and von Neumann, J. 1950. Numerical integration of the barotropic vorticity equation.. *Tellus*, 2, 237-254
- Clarke, R.G. and Strickler, R.F. 1972. Southern hemisphere prediction with a nine-level, primitive-equation model. *Mon. Wea. Rev.*,100, 625-636.
- Cressman, G. 1960. An operational objective analysis system. *Mon. Wea. Rev.*, 87, 367-374.
- Davidson, N.E. and McAvaney, B.J. 1981. The ANMRC tropical analysis scheme. *Aust. Met. Mag.* 29, 155-168.
- Davidson, N.E. and Puri, K.K. 1992a. Limited area prediction for AMEX. *Aust. Met. Mag.*, 40, 179-190.
- Davidson, N.E. and Puri, K.K. 1992b Tropical prediction using dynamical nudging, satellite convective heat sources, and a cyclone bogus. *Mon. Wea. Rev.*, 120, 2501-2522
- Davidson, N.E. and Weber, H.C. 2000. The BMRC high-resolution tropical cyclone prediction system: TC-LAPS. *Mon. Wea. Rev.* 128,1245 –1265.
- Gardner, J. 1993. Stormy Weather: A history of the Bureau of Meteorology. M.Sc. Thesis , University of Melbourne (Available in Bureau of Meteorology Library as originally submitted and in an abridged version with slightly altered title as *Bureau Metarch* papers No. 11, 1997)
- Guymmer, L.B. 1977. Operational application of satellite imagery to synoptic analysis in the southern hemisphere. *Tech Rep. No. 26*. Bur. Met. Australia 83 pp
- Gauntlett, D.J. 1974 Ph.D Thesis , University of Melbourne
- Gauntlett, D.J., Seaman, R.S., Kininmonth, W.R., and Langford, J.C. 1972. An operational evaluation of a numerical analysis-prognosis system for the southern hemisphere. *Aust. Met. Mag.* 20, 61-82.

- Harris, B.R. and Kelly, G.A. 2001. A satellite radiance bias correction scheme for data assimilation. *Q.J. Roy. Met. Soc.* 127,1453-1468.
- Hart, T.L., Bourke, W., McAvaney, B.J., Forgan, B.F. and McGregor, J.L. 1990. Atmospheric general circulation simulations with the BMRC global spectral model: The impact of revised physical parameterisations. *J. Climate*, 3, 436-459.
- Hart, T.L., Bourke, W.P., Steinle, P.J. and Seaman, R.S. 1993. Impact of higher resolution satellite soundings of temperature and moisture on medium range prediction. *Mon. Wea. Rev.* 121, 1746-1758.
- Kelly, G.A., Mills, G.A. and Smith, W.L. 1978 Impact of Nimbu-6 temperature soundings on Australian region forecasts. *Bull Am. Met Soc.* 59, 393-405
- Le Marshall, J.F., Davidson, R.F., Willmot, M.C. and Powers, P.E. 1989. A physically based operational atmospheric sounding system for the Australian region. *Aust. Met. Mag.*, 37, 193-199.
- Le Marshall, J.J., Pescod, N., Khaw, A. and Allen, G. 1993. The real-time generation and application of cloud-drift winds in the Australian region. *Aust. Met. Mag.*, 42, 89-103.
- Le Marshall, J.F., Riley, P.A., Rouse, B.J., Mills, G.A., Wu, Z.-J., Stewart, P.K., and Smith, W.L. 1994. Real time assimilation and synoptic application of local TOVS raw radiance observations. *Aust. Met. Mag.*, 43, 153-166.
- Leslie, L.M. and Dietachmayer, G.S. 1992. Real-time limited area numerical weather prediction in Australia: a historical perspective. *Aust. Met. Mag.*, 41, 61-77
- Lynch, P. 1993. Digital filters for numerical weather prediction. *HIRLAM Technical report No. 10*, (Helsinki, Finland), 52 pp.
- Maine, R. 1966. Automatic numerical analysis for the Australian region. *Met Study. No 16*, AGPS Canberra 156pp.
- Maine, R. and Seaman, R.S. 1967. Developments for an operational weather analysis system in the Australian region. *Aust. Met. Mag.* 15, 13-31.
- Mills, G.A. and Davidson, N.E. 1987. Tropospheric moisture profiles from digital IR imagery; System description and analysis/forecast impact. *Aust. Met. Mag.* 35, 109-118.
- Mills, G.A. and Seaman, R.S. 1990. The BMRC regional data assimilation scheme. *Mon. Wea. Rev.* 118, 1217-1237.
- Mills, G.A. and Russell, I. 1992. The April 1990 Floods over Eastern Australia; Synoptic discussion and assessment of regional NWP guidance.
- Naughton, M.J. and Balgovind, R.C. 1990, BMRC Implementation of the NCAR CCM modular processor. *BMRC Research Report*, June 1990, 37 pp.
- Noar, P.F. and Young, J.R. 1972. The CMRC optimised filtered baroclinic model. *CMRC Internal Scientific Report 16*.
- Puri, K. K. Normal Mode Initialisation in the ANMRC data assimilation scheme. 1981. Proceedings of the (fourteenth) Stanstead Seminar. McGill University.
- Persson, A, 2004. Early Operational NWP outside the USA (to be published).
- Puri, K. and Bourke, W.P. 1982 A scheme to retain the Hadley circulation during non-linear normal mode initialization. *Mon. Wea. Rev.*, 110, 327-335.

- Puri, K.K., Davidson, N.E., Leslie, L.M and Logan, L.W. 1992. The BMRC tropical limited area model. *Aust. Met. Mag.* 40, 81-104.
- Puri, K.K., Dietachmeyer, G., Mills, G.A., Davidson, N.E., Bowen, R.M. and Logan, L.W. 1988. The new limited area prediction system, LAPS. *Aust. Met. Mag.* 47, 203-223..
- Rikus, L. 1997. A scheme for validating clouds in an operational global NWP model. *Mon. Wea. Rev.* 125, 1615-1637.
- Seaman, R.S. 1972. Stability-temperature correlations and their applications to objective analysis. *Aust. Met. Mag.*, 20, 83-104.
- Seaman, R.S., Falconer, R.L. and Brown, J. 1977 Application of a variational blending technique to numerical analysis in the Australian region. *Aust. Met. Mag.* 25, 3-23.
- Seaman, R. S. 1993. Monitoring a data assimilation system for the impact of observations. *Aust. Met. Mag.* 43, 41-48.
- Seaman, R.S., Bourke, W., Steinle, P.J., Hart, T.L., Embery, G., Naughton, M. and Rikus, L.J. 1995: Evolution of the Bureau of Meteorology's Global Assimilation and Prediction system. Part 1: Analysis and initialisation.. *Aust. Met. Mag.*, 44, 1-18.
- Seaman, R.S. 1997. An Australian perspective on meteorological analysis and data assimilation since the early 1960s. *Aust. Met. Mag.*, 46, 117-126.
- Seaman, R.S. 1999. Quality control of Australian sea-level pressure observations. *Aust. Met. Mag.*, 48, 123-131.
- Seaman, R.S. 2005. ANMRC- Victim of institutional politics ?. Bureau of Meteorology *Metarch Paper* (in press)
- Smagorinsky, J. , Manabe, S. and Holloway, J.L. 1965. Numerical results from a nine level general circulation model. *Mon Wea. Rev.*, 73, 727-768.
- VR84. CMRC/ANMRC Valedictory Report 1984. (Available in Bureau and CSIRO Libraries)