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PIONEERING OF NUMERICAL WEATHER PREDICTION IN AUSTRALIA: DICK JENSSEN, UWE RADOK AND CSIRAC

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ABSTRACT: Pioneering calculations in atmospheric science were performed at the University of Melbourne in 1957–1959 by the Master of Science student Dick Jenssen under the supervision of Uwe Radok. These studies, using the University of Melbourne computer CSIRAC, were documented in the Jenssen thesis but without any further publication. The detail of the studies has largely been hidden and the aim of this essay is to present an account of these significant studies to a wider scientific community.

Keywords: Numerical Weather Prediction, Barotropic NWP, CSIRAC, Dick Jenssen, Uwe Radok

INTRODUCTION

The year 2019 marked the sixtieth anniversary of significant and pioneering calculations in atmospheric science performed at the University of Melbourne. The calculations were the first demonstration in Australia of what is known as Numerical Weather Prediction (NWP). The calculations were performed by the then Master of Science (MSc) student Martin James Ditmar Jenssen (always known as Dick), under the supervision of Uwe Radok using the University of Melbourne computer known as CSIRAC; the 1959 MSc thesis by Jenssen was titled ‘On numerical forecasting with the barotropic model’. While these pioneering studies are commonly referenced in accounts and discussions of NWP development in Australia, such references are brief, with little acknowledgement of their scope from NWP or computational points of view. The studies were documented in the thesis but without any further publication. One early report of these Jenssen studies was presented by Radok in a colloquium at the School of Physics of the University of Melbourne; a one-page summary of the colloquium (Radok 1958) records that during the presentation Jenssen demonstrated the execution of the calculations on CSIRAC. Accordingly, the detail of the studies has largely been hidden from the wider meteorological community and only recently revealed to the author following access to the Jenssen thesis at the Baillieu Library, University of Melbourne.

Before proceeding to discuss the studies in some detail, this essay proposes to set the scene at that time pointing to a number of contemporaneous events that led to the first Australian step into NWP namely (i) the state of the science of NWP in the 1950s, (ii) the fortuitous availability of the CSIRAC computer at the University of Melbourne, (iii) the initiative of Radok who recommended and supervised the project and (iv) the skill of Jenssen, who had prime carriage of the research program for his two-year MSc studies.

THE STATE OF NWP IN THE 1950s

The science

The history of NWP is extensively documented in many papers and reviews. A notable overview among these is the paper ‘The birth of numerical weather prediction’ by Wiin-Nielsen (1991). This discusses the fundamental theoretical studies by Charney (1948, 1949), which led to the pioneering barotropic model forecasts for the North American region using one of the earliest available computers, known as ENIAC (Charney et al. 1950). Platzman (1979) presents a retrospective and detailed narrative of the events around these ENIAC computations, while a comprehensive account of Charney’s extraordinary impact on meteorology is given by Phillips (1982).

The studies by Charney (1948, 1949) provided a much improved mathematical understanding of the hydrodynamical equations describing atmospheric flow, as Thompson (1978) wrote:

> In 1948 Charney, following a lead that he saw in his own thesis work, published a remarkable paper in which he suggested that a derived form of the hydrodynamical equations be modified in such a way that solutions corresponding to high-speed sound and gravity waves (both of which may lead to computational instability) are excluded, but such that solutions corresponding to the large-scale meteorological modes are retained almost intact.

These advances in the late 1940s provided a way forward from the seemingly intractable problems encountered by Richardson (1922), who had made the extraordinary and rightly legendary attempt, using the full hydrodynamical primitive equations, to predict the surface pressure tendency for two locations in Europe for a period in May 1910. A very comprehensive description and analysis of Richardson's study is presented by Lynch (2006); he describes and analyses Richardson's achievement, pioneering in its complexity of formulation and in the massive manual computation it demanded. Thompson (1978), in an earlier discussion of Richardson's epic work, described Richardson's single monograph as an oddly quixotic work being a candid report of an admitted but glorious failure.

The computer

Apart from the simplifying formulation of the atmospheric model, invoked by Charney and his collaborators in the first successful NWP calculation, the additional essential component was the availability of the electronic computer. Although Richardson's insights were a definitive contribution, the extraordinary volume of manual numerical computation in what he had attempted was so overwhelming that practical NWP could not become possible until the advent of the electronic computer some three decades later.

The computer available at the University of Melbourne for the study by Jenssen was CSIRAC; its history has been extensively documented in the publication edited by McCann and Thorne (2000) and in which McCann writes:

> During 1945 and 1946 ideas on the possibility of electronic computing were hatching in the mind of a young English physicist and mathematician, Trevor Pearcey. Upon his arrival in Australia in late 1945 and his employment in the Council for Scientific and Industrial Research (CSIR), Division of Radiophysics, Pearcey set about to convince others of the need to devote resources to the exploration of these ideas.… In early 1947, Edward Bowen, Chief of the Division (with prompting from Pearcey) decided that Radiophysics should enter the field of high-speed electronic computing.
>
> Initially it was intended that a very simple prototype computer be built to illustrate general principles. This was to be followed by another computer which would be available for general use and provide the basis of a computing service. So, in early 1947 Trevor Pearcey teamed up with Maston Beard who was placed in charge of engineering development. Beard was a graduate in Electrical Engineering from Sydney University and had worked in the Division of Radiophysics during the war. Beard and Pearcey proceeded with the design and construction of the minimum necessary components for an electronic computing system.

This machine, initially named CSIR Mark 1, was designed and developed in the Division of Radiophysics, located on the campus of the University of Sydney This development was largely independent of work then underway in the UK and USA. The CSIR Mark 1 ran its first program in November 1949. It was the fourth or fifth stored program electronic computer in the world and the first outside the UK and USA. The paper by Beard and Pearcey (1984) provides perhaps the most comprehensive description of the genesis and evolution of CSIR Mark 1, together with references to the primary papers by Pearcey, Beard and colleagues on its technical design and its programming. CSIR was reconstituted in 1949 as CSIRO (Commonwealth Scientific and Industrial Research Organisation).

Substantial debate and discussion occurred from 1951 to 1954 within CSIRO and through a Committee on Mathematical Instruments convened to discuss the future of the CSIR Mark 1 facility. The minutes of these meetings are discussed at length by Willis and Deane (2006); the committee had representatives from CSIRO, the universities and government. At the second meeting of the committee in April 1952 the Chief of Radiophysics, Edward Bowen, detailed ongoing discussions that he had in relation to engaging local manufacturers to use CSIR Mark 1 as a prototype for building some further machines. Pearcey reported to this same Committee at their third meeting in September 1952 that 'the CSIRO computer had been operating at considerably less than full capacity due mainly to shortage of staff' and stated that 'the machine had been developed to the state where he felt it could be operated satisfactorily for something like 20 hours per day'. The potential outcomes from Bowen's formal requests made in late 1951 for quotes from three commercial manufacturers, foundered as the anticipated costs were deemed well beyond available funds. Subsequently, in March 1954, Bowen advised CSIRO that 'the continued existence of a large computing section in the laboratory where the main interests now lie in other fields is not satisfactory' (National Archives of Australia, 1954a).

Beard and Pearcey appear to have become fully acquainted in May 1954 with the CSIRO proposal to transfer Mark 1 from the CSIRO Division of Radiophysics. They corresponded with Frederick White, the Chief Executive Officer of CSIRO, presenting extensive arguments for the continued support within CSIRO of the machine, perhaps through the establishment of a separate section within CSIRO, possibly associated with a university (National Archives of Australia, 1954b). Pearcey sought some further advice and guidance by writing to Douglas Hartree (Plummer Professor of Mathematical Physics at Cambridge University, UK) regarding pending decisions on Mark 1. Hartree had been an invited expert at the Conference on Automatic Computing at the University of Sydney (University of Sydney, 1951). Both Hartree and Pearcey each presented several extensive papers at the conference and were in some disagreement on some subtleties of design, such as the enhanced precision of Mark 1. Pearcey (1994) states that at the time of the 1951 conference Hartree had provided to the CSIRO executive a favourable opinion on the concept of forming a special CSIRO computing laboratory. Nevertheless Pearcey's 1954 correspondence with Hartree precipitated further exchanges between Hartree and White, and Hartree and Thomas Cherry (Professor of Applied Mathematics at the University of Melbourne), who had also expressed interest in Mark 1. Hartree's letter in June 1954 to White commented, 'If it (Mark 1) had been completed satisfactorily 2½ years ago, it would have been in the van of progress, and there might then have been a case for going on to Mark II; but I think the time for this has passed' (National Archives of Australia, 1954c). Hartree's letter (University of Melbourne Archives, 19540525) to Cherry provided withering and scathing comments on Pearcey's communication skills with faint praise for his accomplishments, which perhaps accounts for Pearcey ultimately not being involved in the then planned role for Mark 1 at the University of Melbourne. So, with the Chief of his own division, Bowen, and a towering presence of Hartree providing adverse commentary from afar, Pearcey and Beard's hopes for continuing involvement with Mark 1 and a projected Mark II were doomed. After considerable agonising by CSIRO, involving the initial consideration of the machine going to the Aeronautical Laboratories in Melbourne (ARL), the CSIR Mark 1 was transferred from Sydney to the University of Melbourne in June 1955. There, after being reassembled, it was renamed CSIRAC and provided a very successful service from mid-1956 until November 1964.

It is remarkable that Pearcey was not seen to be crucial to the planned management and development of the computational and mathematical applications on the Mark 1 when it was transferred to Melbourne. Earlier, in March 1954, Radiophysics had been considering that both Pearcey and his colleague Geoffrey Hill, who was responsible for extending much of the programming logic and design, rather than Beard, would 'go with machine' (National Archives of Australia, 1954d). However, it was Beard who led the transfer and installation of the Mark 1 in Melbourne; he then resumed his career in the Division of Radiophysics, which included him designing equipment for the Parkes Radio telescope. Hill was eventually seconded to the CSIRAC facility in 1957. Jenssen, in the acknowledgements in his thesis, thanks CSIRAC consulting staff and Hill in particular for many invaluable suggestions in the use of CSIRAC.

A comprehensive account of Pearcey's career is presented by Ainsworth (2014), who recounts that after the demise of his involvement with the Mark 1, Pearcy took leave from CSIRO, taking up appointments in the UK in 1957 for two years before again resuming his appointment within CSIRO in 1959. Ainsworth records that he 'transferred to the Division of Mathematical Statistics to participate in the planning for a computing laboratory for CSIRO. He was located at the Computation Laboratory, University of Melbourne, which also housed CSIRAC at this date'. Philipson (2017) describes Pearcey as the 'driving force behind CSIRO's move into computing, which led to the establishment of the CSIRO Division of Computing Research and CSIRONET established in 1963 as Australia's first computer network'.

In 1983, Barry Jones, as Federal Minister for Science, stated in an address presented at the University of Melbourne:

> It is incredible to reflect that at the end of the 1940s we had what was probably the fourth or fifth largest stored memory computer anywhere in the world; CSIRAC which adorned this University for many years. Then, there was a decision in 1951 that computers weren't really going to get anywhere, and they were just really glorified toys. The money that was to have been allocated to further computer development was literally the money that was then ear-marked for the cloud-seeding project which went on for 30 years with negative results (Jones 1983).

Willis and Deane (2006) analyse in great detail the management decisions by CSIRO to discontinue the Mark 1 computer development, asking whether it was 'a lost opportunity'. They concluded that the decision to cease computer development in CSIRO reflected the economic situation at the time.

After its decommissioning in 1964, the CSIRAC computer was disassembled and put in storage, to be preserved by the Museum of Victoria. It has been subsequently reassembled and, after being at several locations in Melbourne, is now in repose at Museums Victoria's Scienceworks campus in Spotswood, where some flashing lights hint at a sense of its former glory (Figure 1).

The Australian scientists Radok and Jenssen

Uwe Radok (Figure 2) was one of a distinguished group of German scientists who had a remarkable impact on meteorology research in Australia (Zillman 2015). The history of his path to Australia is quite extraordinary. He grew up in Konigsberg, East Prussia, attended school there and in his late teens became interested in aeronautical

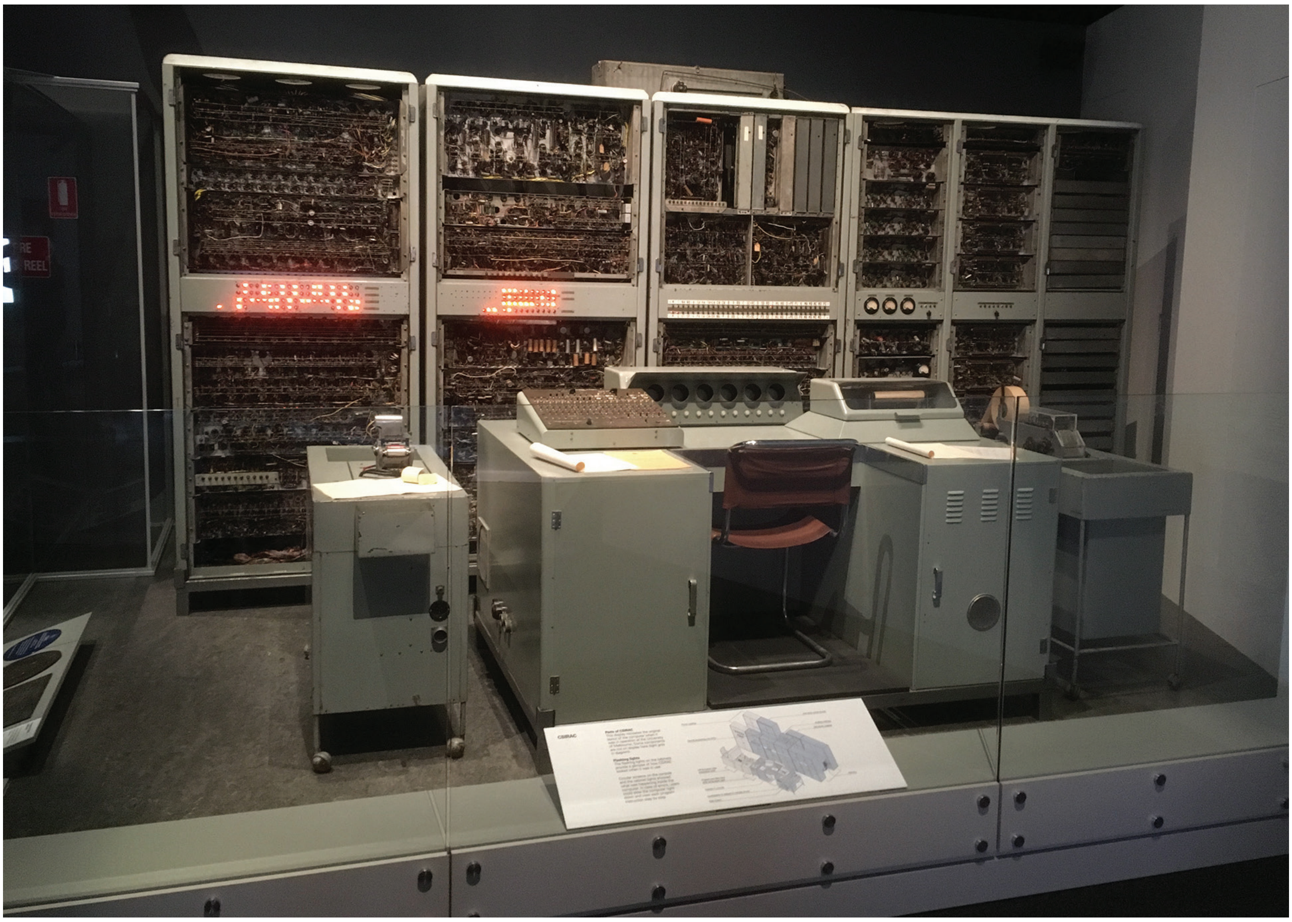

Figure 1: The CSIRAC computer as reassembled most recently in 2018 and located on display at Scienceworks (Museums Victoria). Photograph by William Bourke.

meteorology through a glider-training program. He completed his degree in Mechanical Engineering in Munich, and fled Nazi Germany in 1938 to seek work in Scotland. Along with thousands of other refugees in the UK, he was interned as an enemy alien in early 1940.

The subsequent events are described in *Dunera Lives, A Visual History* (Inglis et al. 2018) and are summarised here. Radok was on board the SS Arandora Star with other internees, including his two brothers, bound for internment in Canada, when it was sunk by a German U-boat, with extensive loss of life, off the coast of Donegal, Ireland. The Radok brothers all survived but found themselves, along with 450 survivors of the SS Arandora Star, one week later on 10 July 1940 aboard another internee ship, HMS Dunera; this group of approximately 2500 men were being transported to an unknown destination. The 'Dunera Boys', as they have subsequently become known, were destined for Australia, where they were interned in a number of remote camps, with the three Radok brothers being interned in Tatura in northern Victoria in September 1940. Inglis et al. (2018) provide a powerful account of the lives of the 'Dunera Boys' in internment, with several references and illustrations relating to the Radok brothers. One reference of some irony states, 'The seven members

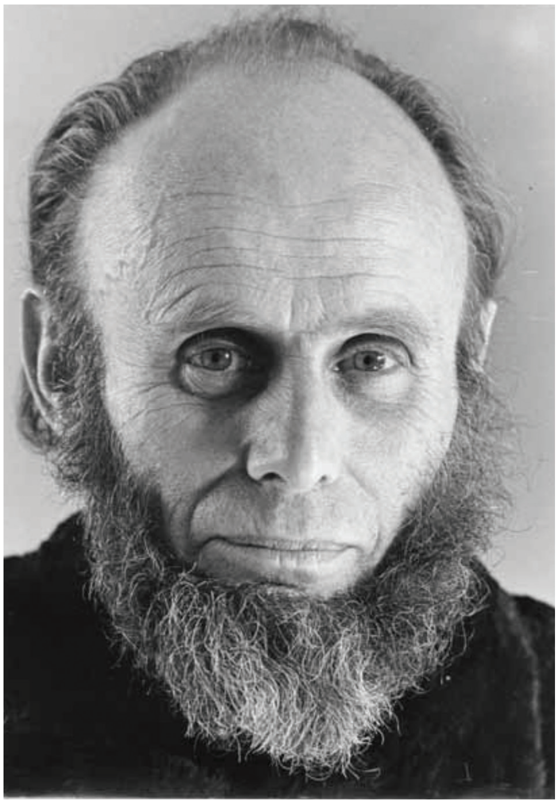

Figure 2: Uwe Radok (1916–2009). (Photo by Helmut Newton, Courtesy of Jacquie Houlden.)

of the Radok family had been granted entry permits by the Australian government in August 1939, but the coming war prevented their migration'. A second volume, *Dunera Lives, Profiles* by Inglis et al. (2020), is focused on the lives of particular individuals from the Dunera cohort; the authors note in their introduction that 'fewer than 700 — a minority of the population that wound up in Australian internment — stayed in Australia'. The photograph shown in Figure 2 was taken by the renowned photographer Helmut Newton, who was a fellow internee in Tatura and a close friend of Uwe Radok.

Some of the internees were eventually released after 18 months at Tatura and were allowed to enlist in the Australian army, serving for approximately a further two years. Radok (1993), in an appendix to his history of meteorology at the University of Melbourne, recalls:

> After Pearl Harbor we were released from internment to become soldiers in a special company employed for the uniquely Australian task of transferring freight from Victorian-gauge rail-cars into others running on the New South Wales gauge, and vice versa.

After discharge from the army, Radok was appointed as a technical assistant in the Department of Meteorology at the University of Melbourne, where he completed his PhD, under supervision of Fritz Loewe, and went on to become Head of the Department in 1961 (Zillman 2015). Zillman writes that Radok:

> …worked tirelessly to build international linkages for his research students from the Bureau [of Meteorology] and CSIRO. But despite his own prodigious scientific output and the high regard in which he was held by all his former students and colleagues, he was never promoted to professor and he spent his final years at Melbourne feeling unrecognised and unappreciated. When his post was eventually upgraded to professor, rather than apply for his own position, he left to spend the last working decade of his highly productive meteorological career in the United States (Boulder, Colorado).

Radok's research indicates he was very well informed on developments in NWP in the 1950s in the USA and Europe. He presented a seminar in Melbourne in March 1957, titled 'Towards numerical forecasting for the Australian region', alluding to computations which were being currently prepared with his MSc student Jenssen using CSIRAC. Radok indicates that he had been slowly learning to use CSIRAC at the time when Jenssen applied for the MSc research scholarship (Radok 1993).

In addition to his meteorological research, he established an internationally respected research program focussed on Antarctic glaciology. A comprehensive review of Australian glaciologist's research in Antarctica has been published by Antonello (2018), who states 'The work of Budd, Radok and Jenssen created a virtual whole ice sheet in the Melbourne computer, and in the process truly cemented Melbourne's place as a leading glaciological centre. Though their work was published throughout the decade, the significant articulation of it came in 1971, with their monograph "Derived Physical Characteristics of the Antarctic Ice Sheet" (Budd et al. 1971)'. In recognition of Radok's contributions to the science of Antarctica, Radok Lake and the Radok automatic weather station, both in Antarctica, have been named after him.

Dick Jenssen was born in Shanghai in 1935. The family moved to Sydney in 1941, with Jenssen and his Russian mother leaving initially and his British father, a Shell Oil employee, managing to exit a little later on the last ship prior to the Japanese invasion. Jenssen grew up in Melbourne, completing his Bachelor of Science (BSc) course at the University of Melbourne, majoring in physics at a time when meteorology was not part of the physics undergraduate program. Subsequently the School of Physics and the Meteorology Department, while half a campus apart, collaborated to the extent that third-year physics courses incorporated an option for units of nine lectures in meteorology. During the 1950s, the School of Physics was obsessed with nuclear physics, having several largely homemade accelerators. Jenssen applied for and was accepted as a Masters candidate in the Meteorology Department under the supervision of Uwe Radok. His research topic was 'The barotropic model', a simplified set of equations describing the mid-troposphere motion of the atmosphere, and which allowed prediction of the atmospheric flow using an electronic digital computer.

From the brief histories above it can be seen there was a remarkable convergence of events: CSIR Mark 1 found its way to the University of Melbourne following perplexing decisions within CSIRO; Uwe Radok and his brothers survived being torpedoed and 18 months of internment as aliens during the war; and the young Dick Jenssen and his parents escaped Shanghai just prior to the onset of the war in the Pacific. Although a graduate of the University of Melbourne School of Physics, where nuclear physics reigned supreme, Jenssen chose post-graduate study in meteorology. After his serendipitous learning of a possible project in meteorology, his first impressions were that it seemed 'about as interesting as the physics and chemistry of doughnuts'; however, with access to this new digital electronic computer CSIRAC, he considered that he was in 'seventh heaven' and 'the planned MSc project was going to be like *living a science fiction story*' (private communication). He was and remains to this day an avid fan of science fiction and was a founding member of the

Figure 3: Dick Jenssen, at the reassembled CSIRAC computer in 1999, recapturing a photo published in a Melbourne newspaper in September 1958. (Photo courtesy of Peter Thorne.)

Melbourne Science Fiction group in 1952. His science fiction involvement saw the annual award of the Australian Science Fiction Foundation, to become known, in 1969, as the Ditmars (after his favourite Christian name). Figure 3 shows him at the console of the re-assembled CSIRAC, recapturing in retrospect in 1999, a photograph from a *Sun* newspaper report, in September 1958, on the Jenssen and Radok research results.

Jenssen then completed his PhD at the University of Melbourne in 1963, titled 'Application of digital computers to weather analysis and forecasting and to problems of the Antarctic water budget'. He subsequently accepted an invited appointment at the Meteorology Department of the University of Wisconsin from 1963 to 1966, before returning to research and teaching in the Meteorology Department of his former University in Melbourne. His ongoing research continued the pioneering computer modeling begun in his PhD program, focusing on glacial dynamics and thermodynamics of Antarctica.

THE JENSSEN MSc THESIS

In the introduction to his thesis Jenssen states:

> The present work was conceived at the Meteorology Department of the University of Melbourne when an electronic digital computer was installed in the School of Physics. The size of this machine excluded, from the start, any but a barotropic model. However, the choice of the latter was dictated equally by the need for exploratory work regarding the adequacy of upper-air data and the special characteristics of the Australian region.

The mathematical formulation of Jenssen's prediction model was to follow the barotropic model strategy pioneered by Charney et al. (1950). Thompson (1978) paraphrases Charney's insight stating:

> Charney showed that the fundamental dynamical law governing the large-scale motions of the atmosphere is the principle of absolute vorticity conservation,

which states that the product of the vorticity (or spin) of a fluid element around its vertical axis and the area of its horizontal cross-section remains constant with time. (This is in fact, the same mechanical principle by which ballet dancers and figure-skaters go into a rapid spin, starting out with their arms and legs extended and then pulling them in to nearly vertical positions.)

In a barotropic model of the atmosphere, the magnitude and direction of horizontal wind are assumed to be the same at all heights. A less restrictive approximation assumes that the magnitude of the wind can vary with height and that there is one particular height at which the wind field represents a good approximation to the vertically averaged wind field; this height is referred to as the equivalent barotropic level. Such a level was a broadly accepted concept in the northern hemisphere, as enunciated for example by Charney and Eliassen (1949), who wrote that such an assumption makes 'it possible to deal with the large-scale motion approximately as a two-dimensional problem'. This avoided the then unresolved complexity of the full hydrodynamic equations as considered by Richardson (1922).

At the time that Jenssen was commencing his studies, Radok (1957) presented a colloquium where he summarised theoretical work in NWP, with particular focus on the barotropic model. He commented that observational data deficiencies, particularly in the southwest of the Australian region, were expected to be a problem but 'their true extent can only be judged from actual computations which are being prepared for the CSIRAC computer at Melbourne University'. At this same seminar, another distinguished German meteorologist, Andrzej Berson, who lived in Australia following his 1952 appointment to CSIRO (Zillman 2015; Berson 1991), emphasised it could be important to experimentally determine the equivalent barotropic level for the atmosphere in the Australian region.

The comment by Berson at the colloquium by Radok (1957) is taken as the stimulus for Jenssen to devote substantial effort in justifying the concept of an equivalent barotropic level in the Australian region. To confirm the notion of this level applying in the southern hemisphere, Jenssen undertook an assessment of vertical averaging of the atmosphere over five layers from 1000–100 hPa for the Australian region for 20 days in November 1956. A visual analysis of the averaged flow patterns indicated that the mid-atmosphere level at the 500 hPa level 'does indeed give the best approximation to the integrated atmosphere: but for a few cases the 600 hPa level seemed a better fit'. A quantitative analysis of variance in the charts for three of the days was performed and it confirmed that 'a level not too far from 500 hPa represents an equivalent barotropic level particularly for the zonal flow'; a final nomination of 500 hPa as the equivalent barotropic level was made for the thesis study. These results agreed with those of Charney (1949) who had shown that the pressure of this level is likely to lie in the range of 500–600 hPa.

The meteorological analyses data used by Jenssen were from manual analyses by the Bureau of Meteorology for the Australian region of geopotential height at the levels of 900, 700, 500, 300 and 100 hPa. These data were then digitised manually, interpolating the values to the grid-points defined on the Australian region Lambert conformal grid, which is described in the following section.

ATMOSPHERIC MODEL

Jenssen includes in his thesis the details of the barotropic model of Charney et al. (1950), which forms the fundamental framework for his studies. In the bulk of this essay, the Charney et al. (1950) model is referred to as barotropic for brevity, although strictly it is a quasi-geostrophic equivalent barotropic model. This formulation also invokes the approximation that the Coriolis force (the apparent force viewed in the Earth's rotating coordinate frame) and the atmospheric pressure gradient are in balance and yields an expression for the rate of change of the height $\boldsymbol{Z}$ of the 500 hPa mid-troposphere constant pressure surface field as follows:

$$\frac{\partial\,[\nabla^2 Z]}{\partial t} + J\left(Z, \frac{g}{f}\nabla^2 Z + f\right) = 0 \qquad (1)$$

Here $\nabla^2 Z$ denotes the second spatial derivative in the horizontal of Z; f denotes the Coriolis parameter as a function of latitude and the Earth's rotation rate; g denotes the acceleration due to gravity; and J, the Jacobian operator, denotes in cartesian co-ordinates, for example, the non-linear operator

$$J(a, b) = \frac{\partial a}{\partial x}\frac{\partial b}{\partial y} - \frac{\partial a}{\partial y}\frac{\partial b}{\partial x}$$

So, we see equation (1) is a prognostic tendency for the quantity $\nabla^2 Z$, in terms of a non-linear function of Z and f as in the Jacobian. Once the tendency is evaluated, a new value of $\nabla^2 Z$ can be estimated by a finite-difference in time and the remaining but non-trivial task is to evaluate an updated Z from the updated $\nabla^2 Z$.

Jenssen in the main study of his thesis implements the numerical solution of equation (1); he additionally discusses the implications of the geostrophic approximation following Shuman (1957), who identified a systematic prediction error of spurious anticyclogenesis in the classic model as given by equation (1). The cause of this problem arises since equation (1), while derived on the principle of the conservation of the spin or rotational component of the wind flow, also has an implied component of spurious

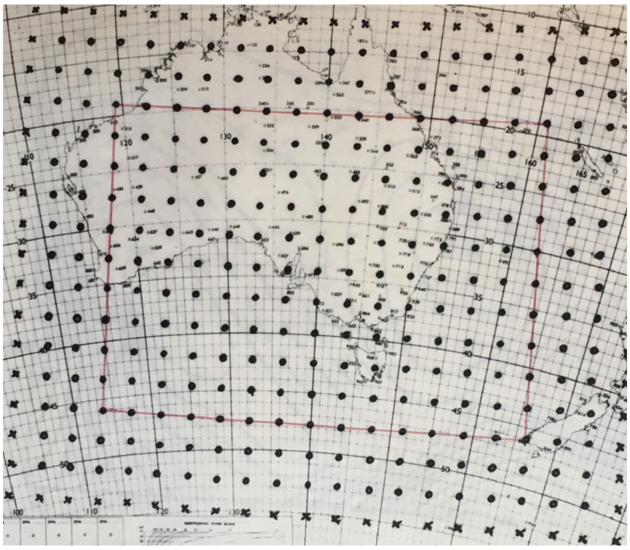

Figure 4: The finite difference grid used in the Jenssen Barotropic model.

divergent or non-rotational flow. Schuman suggested, and demonstrated as a remedy, the imposition of a constraint that formally makes the geostrophic wind purely rotational. In his thesis Jenssen follows this strategy and shows that the $\boldsymbol{Z}$ of equation (1) can be replaced by a purely rotational wind field represented by the streamfunction $\boldsymbol{S}$ of the geostrophic wind, yielding

$$\frac{\partial\,[\nabla^2 S]}{\partial t} + J(S, \nabla^2 S + f) = 0 \qquad (2)$$

Shuman's strategy explicitly retrieves $\boldsymbol{S}$ from the defined geostrophic wind while Jenssen chooses to make the further approximation in equation (2) with the streamfunction retrieved from a simpler expression,

$$\nabla^2 S \approx \frac{g}{f}\,\nabla^2 Z \qquad (3)$$

and refers to this as the pseudo geostrophic streamfunction model.

A further approximation can be made with $\boldsymbol{f}$ in equation (3) replaced by a mid domain constant value f_c yielding then from equation (2)

$$\frac{\partial\,[\nabla^2 Z]}{\partial t} + J\left(Z, \left(\frac{g}{f_c}\nabla^2 Z + f\right)\right) = 0 \qquad (4)$$

Jenssen refers to equation (4) as the pseudo streamfunction model and the essential difference between this pseudo streamfunction model and the classic Charney et al. (1950) barotropic model as given by equation (1) turns out to be the selective use of a constant value of the Coriolis parameter in defining $\frac{g}{f_c}$. Shuman in a footnote to the 1957 paper also pointed out that the solution of equation (2) and the alternative use of approximations yielding non-divergent estimates of the wind field resolves the spurious anticyclogenesis issue.

NUMERICAL METHODS

The mathematical solution of Jenssen's implementation of the barotropic model was obtained by finite-difference methods, as of course there is no analytic solution of this non-linear equation. These finite difference formulations are described by Jenssen in some detail, with a particular focus on what was achievable on CSIRAC with its limited memory and its speed of calculation. The solution was implemented for the Australian region on a rectangular 21 (east–west) x 17 (north–south) grid on a Lambert conic conformal map (a flat projection of the Earth's spherical surface) with approximately 300- km grid-point spacing in mid-latitudes, as shown in Figure 4. The equations as formulated above transform on the map projection to include map scale factors $\boldsymbol{m}$ such that

$$\nabla^2 Z = m^2\,\nabla^2_{map} Z \quad \text{and} \quad J\left(Z, \frac{g}{f}\nabla^2 Z + f\right) = m^2\,J_{map}\left(Z, \frac{g}{f}\nabla^2 Z + f\right)$$

The finite difference representation of model equation (1) at each grid-point of a grid as in Figure 4 could be considered in terms of a set of simultaneous equations. However, this is not practical and so an iterative solution is appropriate for such problems, generically known as a Poisson problem, the task being to evaluate $\boldsymbol{Z}$ having predicted the value of $\nabla^2 Z$ at each grid-point following successive time-steps in the time integration process. The procedures used are broadly referred to as iterative or Richardson relaxation techniques, where an initial estimate of $\boldsymbol{Z}$ is used as a trial value to evaluate the updated quantity $\nabla^2 Z$. This results in a residual, and an appropriate multiplier (referred to as an over-relaxation factor) is applied to this residual as a correction to successive trial values in a series of iterations until convergence is achieved. The convergence rate can be improved by a range of procedures. In particular, Jenssen adopted the extrapolated Liebmann method (Frankel 1950) to optimise this over-relaxation factor and additionally used the current and prior time-step values of $\boldsymbol{Z}$ to estimate an improved first guess to commence the iterative procedure.

A more direct solution of this Poisson problem was implemented by Charney et al. (1950), where the use of a double Fourier series was invoked in conjunction with the use of a finite difference five grid-point stencil treatment of the $\nabla^2 Z$. This requires, at some computational cost, Fourier transforms of the Jacobian term and an additional inverse transform. Jenssen provides a detailed assessment of the number of arithmetic operations involved in this approach but states the overhead of the transforms would be excessively time-consuming on CSIRAC, even with the recognition of symmetries intrinsic to the transforms that yield some efficiency gains. (The Fast Fourier Transform of Cooley and Tukey (1965) was not established at the time of the thesis studies.)

Two papers on improving the efficiency of the finite difference Poisson solver (Flanders & Shortley 1950; Shortley 1953) came to Jenssen's attention and he devoted a considerable amount of his study to an examination of the scope for improving the efficiency of his calculations. Shortley (1953) demonstrated a test calculation for solving the Poisson problem on a 5 x 5 grid with a known exact solution, using what is termed the accelerated Chebyshev iteration. For this well-defined test-case, Jenssen compared the accelerated Chebyshev acceleration along with the Richardson relaxation technique and the extrapolated Liebmann scheme and states that the accelerated Chebyshev scheme (alternating with the extrapolated Liebmann scheme) provided improved accuracy and convergence, although only marginally so. In further comments Jenssen notes that the accelerated Chebyshev scheme includes the additional use of a low-resolution grid on which to apply the pre-calculated Chebyshev operators; this was prohibitive in his studies given the constraints already on the available CSIRAC memory when applied at the resolution 21 x 17 grid of the barotropic model calculations.

In the limited area domain of the barotropic model calculations it is necessary to prescribe boundary conditions; here Jenssen adopted the strategies used by Charney et al. (1950) whereby the tendency, as in equation (1) above, is put to zero at inflow boundary points and extrapolated from the interior at outflow boundary points. The time integration scheme used follows that proposed by Bolin (1955) and a time-step of 1.5 hours was used in the Jenssen studies.

CSIRAC CHARACTERISTICS

Aspects of the logical and physical design of CSIRAC are summarised by Thorne (2014). Key features were the use of a word length of 20 bits and provision for 1024 memory locations, with a cycle time of 960 microseconds, which supported an execution rate of approximately 500 instructions per second. The logical design was essentially completed in 1947. CSIR Mark 1 was implemented using about 2000 vacuum tubes. The computer console included a set of six 50 mm diameter Cathode Ray Tube (CRT) display screens which enabled examination of all memory locations, arithmetic registers and the list of the 16 most recently executed instructions. Execution could be paused at a pre-determined instruction and a single-step capability, was an aid to debugging.

Thorne (McCann & Thorne 2014: 62) comments on the location of CSIRAC in the School of Physics and the impact on CSIRAC and possibly associated staff of the School's devotion to nuclear particle accelerators at that time:

> In the Laboratory, on one side, there was a Van de Graaff style of generator, called the Statitron … It generated about 600,000 volts on one of those big globes that could spark to ground. When it did spark to ground, pulses appeared in CSIRAC's memory – extra bits grew in the memory. On the other hand, across the walkway out-side there was a cyclotron. When they turned on the cyclotron the power used to go down, and you were likely to lose pulses and bits out of the memory. We were also actually in a radioactive area; there were parts of the Laboratory where you were not supposed to linger, particularly when some of the neighbouring Physics Department equipment was working, because the radioactivity levels were above those recommended.

The primary memory provided by a mercury acoustic delay line was designed with 1024 words, accommodating program instructions as well as data; in the Jenssen studies only 640 words of the primary memory store were routinely available for use. Additional backing storage on a magnetic drum, with a capacity of 1024 words, was also available on CSIRAC. A further detailed description of the facility and its usage is given by Deane (1997) who describes using CSIRAC as follows:

> The Mark I did not have an operating system which started automatically … The user was presented with a machine with empty memory and a bank of buttons and switches … The Mark 1 could add, subtract and multiply but it needed a special routine to allow it to do division. Other routines were provided to allow for the use of numbers in scientific notation, trigonometric functions, logs, square roots, complex number manipulation … This was a user-friendly computer.

A first step in commencing to use the machine was to read from punch-paper tape a primary bootstrap tape, followed by a control program required to take the user program and any of the required subroutine libraries on paper tape and store them in memory. The user program was punched on 12-hole paper tape using a unique typewriter capable of representing the mnemonic syntax of the available CSIRAC commands. The users prepared requisite input data punching to a 5-hole paper tape. Program debugging was assisted by the ability to display contents of data registers and commands in memory on the cathode tube displays.

The programming language for CSIRAC was simplified in Melbourne relative to that initially implemented in Sydney on the CSIR Mark 1 (Deane, 1997) and this Melbourne strategy of coding was used by Jenssen. (The article by Deane includes considerable detail on the history of CSIRAC, its hardware and logic design and also its programming language.) A programming manual for CSIRAC by Pearcey and Hill, based on their joint papers and developed and published by the University of Melbourne Computation Laboratory (Programming Manual, 1959), provided a comprehensive documentation for CSIRAC users.

To convey some small insight into some of the challenges in using CSIRAC, it is informative to consider how multiplication was handled. In multiplication, three arithmetic registers were used with the resultant product located in concatenated registers as a 38-bit word, which was then truncated to 20 bits. A convention was necessary to define, for example, the location of the decimal point of the resultant product. Jenssen in his studies chose to place the implied decimal point of his representation of the key variable ***Z***, the geopotential height, in between the 10th and 11th digits of the 20-bit word. Accordingly, multiplications required a clear knowledge of the scaling of resultant products and the use of right and/or left shifting was necessary to maintain the implied decimal point in the correct position throughout calculations. Jenssen (private communication) described his strategy to the author as follows: ‘I single-stepped through the code *multiple times* to ensure that my commands did what I wanted them to do, and that the results of the computation were of the right magnitude, and that I preserved accuracy to be as high as possible while covering all cases’.

Jenssen included in the appendix to his thesis copies of the programs he developed for his studies; the interested reader can access the thesis at the University of Melbourne for further details.

Jenssen summarises some of the practical matters encountered in using CSIRAC:

- The console enabled interaction with the program via a set of switches on which values of program parameters may be set, as for example the relaxation factor of the Liebmann solver and the accuracy level required for the iteration.
- With the slow speed of the machine, lengthy calculations were subject to random errors arising from power fluctuations giving rise to non-trivial errors. Errors were manifest for example by an excessive number of iterations in the Poisson solver.
- A procedure for monitoring the progress of calculations was developed using a CRT display of 16 special registers; with each register holding a 20-bit word this yielded a 20 x 16 bit map as shown in Figure 5. Jones (2020) describes this development by Jenssen as ‘some of the first significant computer generated graphic data visualization in Australia’.

Figure 5: CRT image display of a 500 hPa height field with an overlaid outline of the Australian continent.

THE MODEL PREDICTIONS

Available charts of manual analysis from the Bureau of Meteorology were digitised and used to initialise the model for 4 June 1957 at 2300 GMT, with the subsequent 24-hour analysis for 5 June 1957 at 2300 GMT, similarly digitised and used for qualitative verification. The charts for the initial condition and that of the 24-hour validating analysis are shown in Figures 6a and 6b, along with the change in height from the initial condition in the ensuing 24 hours in Figure 6(c); note the contours in Figures 6(a) and (b) are in hundreds of feet, while Figure 6(c) shows contours at 20-metre intervals. This evolution shows a low-pressure trough approaching from the south-west with ridging over south-eastern Australia and into the Tasman sea.

The numerical predicted changes shown and discussed in the thesis include the following:

(1) the barotropic model for 6, 12 and 24 hours, equation (1) above
(2) the pseudo streamfunction model: for 12 hours, equation (4) above
(3) the pseudo streamfunction model with correct boundary conditions: for 12 hours
(4) a test of zeroing the Coriolis parameter: for 6 hours
(5) the pseudo geostrophic streamfunction model for 12 hours, equations (2) and (3).

Jenssen points out that most of these forecasts were for periods of 12 hours because of the difficulty encountered with CSIRAC of achieving error-free run-times of the 4 hours required for a 24-hour forecast.

The 6, 12 and 24 hour forecast changes with the barotropic model (equation 1) are shown in the thesis. The forecast charts of the thesis were shown only for the inner (red-rimmed) area of Figure 4, to avoid spurious domain boundary effects. The pioneering and the first Australian execution of this model's 24-hour forecast changes are shown in Figure 7. This calculation was completed on 8 September 1958.

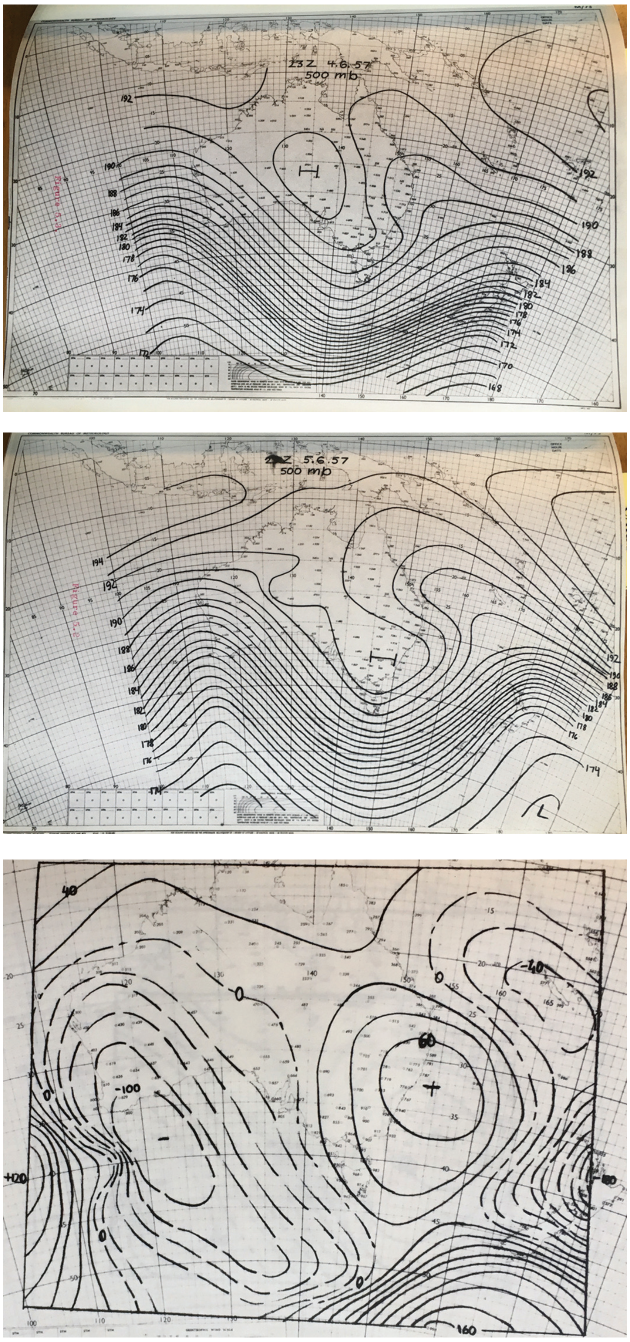

Figure 6: 500 hPa geopotential height in the Australian Region of:
(a – top) Analysis for 2300 GMT on 4th June 1954. Contour interval is hundreds of feet.
(b – middle) Analysis for 2300 GMT on 5th June 1954. Contour interval is hundreds of feet.
(c – bottom) Changes in analysis from 2300 GMT on 4th June 1954 over the ensuing 24 hours. Contour Interval is 20 metres.

Jenssen summarises the 24-hour forecast as follows:

> The most remarkable aspect of the 24-hour chart is the sudden intensification of the spurious anticyclone which now becomes centered slightly east of Perth. The rapid generation of this high lends support to the argument of Shuman … Comparing this chart with the true 24-hour height changes it is seen that the main

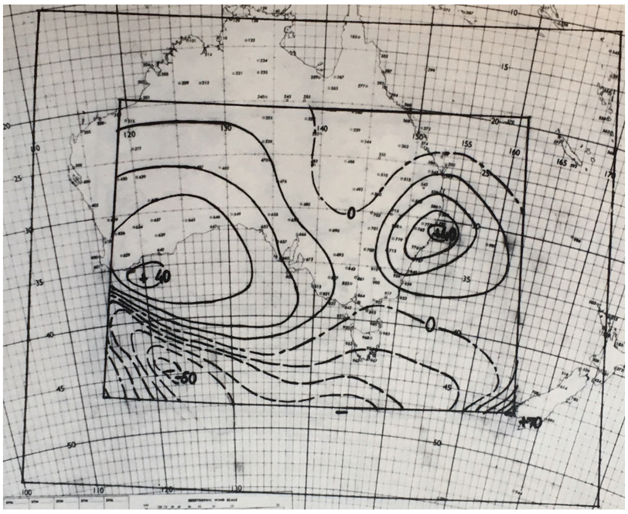

Figure 7: Barotropic model predicted 24-hour changes of the 500 hPa geopotential height field in the Australian region from 2300 GMT 1954. Contour interval is 20 metres.

> difference is the spurious anticyclone which distorts the pattern … The low near Perth has not deepened at all, but the feature over Sydney has intensified.

Jenssen's further diagnosis of the performance of the model was focused on examining 12-hour predictions to assess the differing model formulations that he had implemented; the availability and reliability of CSIRAC precluded extending these calculations to 24 hours. One additional calculation using diagnosed tendencies on the region's boundaries (derived from the initial condition and the subsequent 24-hour verifying analysis) is described as using the 'correct boundary conditions' instead of these boundary conditions being put to zero at inflow boundary points and extrapolated from the interior at outflow boundary points as in all other calculations.

Jenssen includes displays of four 12-hour predictions in the thesis: the barotropic model (equation 1); the pseudo streamfunction model (equation 4); the pseudo streamfunction model with 'correct boundary conditions'; and the pseudo geostrophic streamfunction (equations 2 and 3) but with the usual fixed boundary conditions. A validating display of the observed 12-hour changes was presumably not available, with the Bureau of Meteorology analyses only being digitised for these studies at 24-hour intervals. The barotropic model prediction for 12-hours, shown in Figure 8(a), exhibits the tendencies already seen in the original 24-hour prediction shown in Figure 7. The pseudo streamfunction model (Figure 8b) shows some reduction in the tendency to anticyclogenesis over south-western WA as expected from the Shuman (1957) analysis. However, the change in model performance using 'correct boundary conditions' is quite remarkable with almost complete elimination of this anticyclogenesis over the south-west as seen in Figure 8(c). Furthermore the use

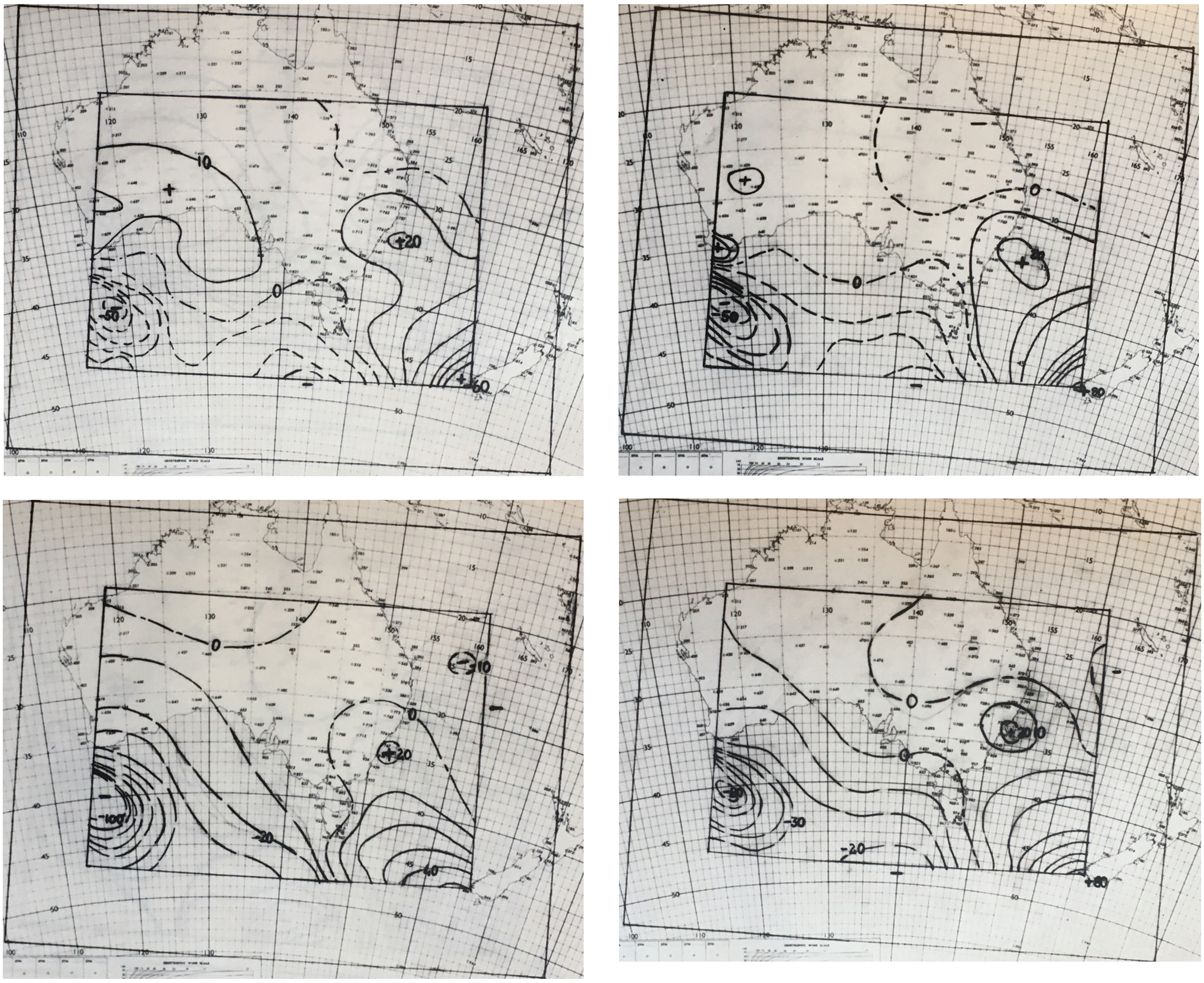

Figure 8: Predicted 12-hour changes of the 500 hPa geopotential height field in the Australian region from 2300 GMT 1954 (contour interval is 20 metres):
(a – top left) barotropic model
(b – top right) pseudo streamfunction model
(c – bottom left) pseudo streamfunction model with 'correct boundary conditions'
(d – bottom right) pseudo geostrophic streamfunction model.

of the more complete Shuman formulation of the pseudo geostrophic streamfunction model, as shown in Figure 8(d), appears to match this removal of the anticyclogenesis and additionally reduce the apparent over-intensification of the low-pressure trough in the south-west.

SUMMARY

Jenssen's studies demonstrated that NWP was a distinct possibility for the Australian region and warranted ongoing effort and focus. His work followed closely the formulation of Charney et al. (1950) and referenced the extensive effort devoted to NWP throughout the 1950s in the USA and Europe, but from an Australian perspective. At the time of writing his thesis, several meteorological centres in the northern hemisphere had already put in place operational versions of barotropic model predictions. In the late 1950s in Australia there was no computing infrastructure to support operational NWP and in fact this did not emerge until 1968 when the Bureau of Meteorology acquired its first substantial computing mainframe, an IBM 360.

The quality of the Jenssen and Radok predictions is impressive viewed from sixty years later. There were clearly challenging issues in the implementations and in obtaining sufficiently robust computer time from the CSIRAC facilities; however, the first 24-hour Australian regional barotropic forecast was successfully implemented and demonstrated in these 1957–1959 studies. Some inherent shortcomings with the geostrophic formulation, following Shuman (1957), were successfully explored and it is particularly notable that refinements via the pseudo streamfunction model and the use of 'correct boundary conditions' generated a 12-hour prediction that was very credible. This use of 'correct boundary conditions' foreshadowed the eventual and routine coupling of a regional area model with a larger scale hemispheric model, such as became operational in the Bureau of Meteorology in the early 1970s.

The progress of NWP at the Bureau of Meteorology in Australia after the Jenssen and Radok pioneering demonstration was notable in the 1960s with the development of experimental operational trials of barotropic model forecasting (Maine 1966), together with an automated multi-level numerical analysis of meteorological data for the region by Maine and Seaman (1967). These systems were implemented using the then CSIRO Division of Computing Research facilities located in Canberra and an objective numerical analysis system provided the basis for operational NWP in the Bureau of Meteorology once it had in place its own mainframe by 1968. The analysis system was initially formulated by Maine (1966) as an MSc project at the University of Melbourne under the supervision of Radok.

There is clearly a range of views on Australia's place in the history of pioneering development of computing. The discussion presented here of the decisions that led to CSIRO opting out of further development of the fourth (maybe fifth) stored program computer in the world reflect the later recollections by Pearcey (1994) that it 'withered from lack of internal interest and supportive imagination'. From June 1956 until November 1964, CSIRAC facilities were operable for approximately 30,000 hours supporting 700 projects; the Jenssen study was an early example of the opportunities afforded by CSIRAC.

The serendipitous course of events that saw Uwe Radok, Dick Jenssen and CSIRAC at the University of Melbourne, all in the 1950s, catalysed and delivered a significant Australian achievement. The present author has been particularly impressed with the high scientific quality and great flair that Dick Jenssen showed in his 1959 thesis in the face of non-trivial scientific and technical challenges. His studies defined the commencement of NWP in Australia and highlighted its potential for the Australian meteorological community.

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EPILOGUE

The problem solved by Charney et al. (1950) was perhaps the simplest representation of the dynamics of atmospheric flow that in the 1950s could address the problem of prediction. Jenssen demonstrated through his examination of the Charney et al.(1950) model and several variations to the formulation that indeed these developments were important for Australia.

The field of NWP has evolved in the most unbelievable fashion since the 1950s. This has been enabled by staggering improvements in computing capacity and an almost unbelievable expansion of observational data via polar orbiting and geostationary satellites. The satellite-derived data are of particular value in the southern hemisphere given the vast oceanic areas, which do not support conventional land-based observations. The mathematics of the modeling has itself developed at a similarly staggering pace, as have the procedures for utilising the available observational data. The current generation of models is based on the full hydrodynamical equations reflecting, albeit with additional extraordinary complexity, the pioneering ideas of Richardson, some 100 years prior. The supercomputers available to NWP also use a substantial amount of time iteratively adjusting the model representation of the state of the atmosphere, typically over a time window of 6 hours, thereby matching all of the available observations in a procedure referred to as four-dimensional assimilation.

The state of the art in NWP some 70 years after Charney et al. (1950) sees many operational centres around the world, including the Australian Bureau of Meteorology, running very sophisticated assimilation systems and model predictions for the globe typically out to 10 to 15 days and in some cases beyond. Some of these models also include a comprehensive assimilation and prediction system of the ocean, which is coupled to the atmospheric model.

The current Australian Bureau of Meteorology NWP systems model the atmosphere over the globe at a horizontal resolution of 12 km with up to 70 layers in the vertical reaching into the depth of stratosphere. Limited-area versions of the assimilation and prediction systems at horizontal resolutions of 1.5 km, each focusing on six domains centred on the Australian capital cities, are also implemented with their boundary conditions derived from the global model predictions. Major centres in the northern hemisphere support even higher resolutions systems, with some currently foreshadowing 1-km horizontal resolution over the globe. Many centres additionally run global ensemble prediction systems; here up to 50 small perturbations of the initial condition are generated to enable estimates of prediction probabilities from the spread of the differing trajectories of these sets of perturbed model solutions. All centres exchange, in real-time, assimilation and prediction results to support comparative assessment and evaluation.

The progress of NWP has indeed been spectacular in recent decades as evidenced by the high quality of up to ten-day predictions, available twice daily and as shown in the media or as accessible via the internet from a number of international meteorological centres.

Conflict of interest

The author declares no conflicts of interest.

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