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FOREWORD

The Commonwealth Meteorology Research Centre (CMRC)/Australian Numerical Meteorology Research Centre (ANMRC) has been sponsored jointly by the CSIRO and the Department of Science. Some 15 years after formation, decisions taken to disband the Centre in 1981 are now being effected and this valedictory report has been prepared to chronicle the role of the Centre throughout its years. The Centre has been a much discussed experiment in the organization of Australian Government funded research with much learned comment written on or about it. As is the wont in review processes, of which there have been many, much of the assessment of the success of this experiment has been generated from without. In this, the final presentation by the Centre itself, we have attempted to provide a forum for informed external comment, and an opportunity for comment by present and past members of staff.

The substantial implication of our valedictory report is that the Centre has been a very successful research organization with significant national and international achievement. That such an arrangement should be terminated remains a puzzle to the staff of ANMRC, who in turn are not surprised at the bewilderment of international colleagues. Nevertheless the decision has been taken and in addition to our retrospective assessment we offer the prospective view that research in dynamical and numerical meteorology is, and continues to be, important in Australia. We further believe that the major research programs in which the Centre has achieved distinction will survive and transcend the institutional rearrangement and rationalization of meteorology research in Australia. Indeed, as suggested by Mr John Lonergan in his contribution to this report, the future challenge to the new research organizations is very clear: ". . . to give effect to the promise they made that in collaboration they could do at least as good a job as the Centre. When the future work receives the measure of acclaim that ANMRC's work did we can all be content that the promise has been honoured."

The preparation of this report has made demands on a number of people closely associated with CMRC/ANMRC. The origins of CMRC in 1969 have been documented by two of the key figures responsible for its inception. Successive Officers-in-Charge have prepared essays on the years of their stewardships. Distinguished overseas scientists, closely associated with the Centre have provided a northern hemisphere perspective of CMRC/ANMRC. Current Centre staff collaboratively have provided a comprehensive summary of the years of research and many members of staff, both past and present, have responded to invitations to provide informal perspectives on the Centre.

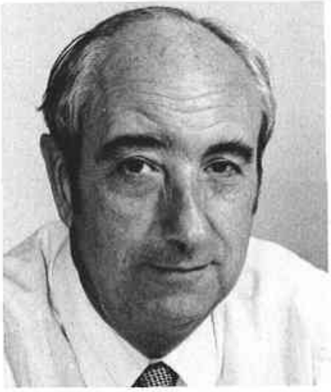
Frances Gauntlett has expertly provided the editorial and organizational skills necessary in the preparation of this report and all present members of staff extend their thanks to Frances.

(William Bourke)
August 1984
Acting Officer-in-Charge

I. ORIGINS OF CMRC

W.J. GIBBS, OBE MSc SM(MIT) Hon DSc (Melb)

Joined Bureau of Meteorology 1939; RAAF Meteorological Service 1941–1946; Assistant Director (Research) 1958–1962; Director of Meteorology 1962–1978; Consultant with World Climate Programme Office, WMO 1980–1981. CMRC Committee 1969–1973, ANMRC Advisory Committee 1974–1978.



C.H.B. PRIESTLEY, AO MA DSc (Cantab) Hon DSc (Monash) FAA FRS

Chief CSIRO Division of Meteorological Physics 1946–1973; Chairman CSIRO Environmental Physics Research Laboratories 1973–1978, Professor of Meteorology Monash University 1978–1980. CMRC Committee 1969–1973; ANMRC Advisory Committee 1974–1979.

Government approval in April 1969 for the establishment of the Commonwealth Meteorology Research Centre was separated by only 18 months from the ICSU/WMO Agreement (October 1967) which formalised the concept of the Global Atmospheric Research Programme (GARP). Historians of meteorology will see this as no coincidence, for the ultimate rationalizations were the same. The national and the international tasks were closely related, and each was large and complex enough, in the eyes of those with the ultimate decision, to require a marshalling of all the appropriate talent which was available at the time.

Thus closed a decade which had been internationally, and in many separate national theatres, one of forward vision and expanding horizons. The potential of the satellite and the computer had engendered a sense of excitement throughout the meteorological world. In his exhortations to the United Nations in 1961 and 1963 to use the advancing technologies to the benefit of mankind, President Kennedy had drawn special attention to meteorology. ICSU and WMO had appointed committees of experts to advise on action in response. The latter had launched the World Weather Watch, the former had begun the design of a global experiment later to become the shared responsibility of GARP. These were much the most ambitious initiatives in world collaboration which any branch of science had ever undertaken. Among Australians we, the authors of this chapter, were the most heavily involved in the preparatory stages and in the best position to arrange for a substantial Australian contribution to the programs.

The Director of the Bureau of Meteorology, Dr Gibbs had proposed to the Government in 1964 that the Bureau should (a) have a substantial increase in staff to meet more adequately the demands for a wider variety and greater complexity of meteorological services; (b) be equipped with a large and powerful electronic computer; (c) accept the invitation to install one of the three World Centres of the World Weather Watch in Melbourne; and (d) have staff of the **Research Scientist** category to strengthen research activities. The Government agreed to (a), (b) and (c) above. The proposal for Research Scientist staff met heavier going and negotiations with the Public Service Board dragged on from 1964 to 1968, during which time the Chairman of CSIRO, Sir Frederick White, and the Chief of the Division of Meteorological Physics, Dr C.H.B. Priestley gave unwavering support. The CSIRO Division of Meteorological Physics, created in 1946, had remained almost constant in size since 1951, with a staff of nine Research Scientists. In 1964 Priestley's submission for a significant expansion was approved by the Executive, having been strongly commended by White and supported by two part-time members, Sir Arthur Coles and Lord Casey.

Together with White, Gibbs and Priestley jointly prepared a "Prospectus for Meteorological Research in Australia" which, on its publication in 1967, revealed our mutual understanding as to the respective roles which the two institutions should follow. At the same time it sought to promote better appreciation in governmental and general scientific circles of the special problems for this area of science. Another of its objectives, the encouragement of meteorology in Australian universities, found response at Flinders University.

In 1968 Gibbs made a further submission based on a wide research panorama drawn up by Dr G.B. Tucker, Assistant Director of Research, and Mr P.V. Moran of the Public Service Board. Despite CSIRO support, the Board remained adamant that Research Scientist positions were not for the Bureau; and word came back that Cabinet would require sharper focus and assurance of CSIRO participation. Accordingly the submission was replaced by a joint one, for the establishment of what we suggested be called the H.C. Russell Research Centre, in memory of the pioneer Australian researcher into the large scale systems of the southern hemisphere. This submission was approved, but the title decided was **Commonwealth Meteorology Research Centre**. Dr Tucker was appointed Officer-in-Charge. The specialities were identified in the formal objectives which read as follows:

> "The work of the Centre would consist of studies of the behaviour of the earth's atmosphere, with emphasis on general circulation, directed towards improvement in understanding the distribution and variations in climate on the earth, and towards improvement in the accuracy and timescale of weather forecasting.

This would include the formulation and testing of numerical hemispheric models, and the modelling of circulations of a more regional type. The approach to these problems would, as desirable, develop the interpretation and use of new forms of observational data. The Centre would not, however, undertake responsibility for observational programmes."

Scientific initiatives taken much earlier had put us in a good position to face up to these objectives. The extension of our horizons could be said to have started with the establishment in the late 1940's of stations at Heard and Macquarie Islands. These were complemented by scientific bases on the Antarctic continent set up and maintained by Australia and other nations, culminating in the International Geophysical Year (1957). They marked the beginning of a permanent data network. Australian analysts had seized these opportunities to develop synoptic techniques and models of atmospheric behaviour in middle and high southern latitudes. Such were to prove of substantial importance to the Melbourne WMC, to the International Antarctic Analysis Centre (IAAC), and later to the CMRC.

The IAAC had been established in Melbourne at the request of ICSU's Special Committee for Antarctic Research. It was sponsored jointly by the Bureau and the Academy of Science with a steering committee composed of the Director of Meteorology (Chairman), Dr Priestley and Dr L.G.H. Huxley. Under the leadership of Mr H.R. Phillpot the Centre achieved substantial improvements in the quality and operational viability of circumpolar southern hemisphere analysis. Subsequently there was a change of emphasis into polar and hemispheric synoptic research before it was disbanded on the creation of CMRC.

Moreover, Australia's research in micrometeorology had been pursued in expectation *inter alia* that surface energy and momentum fluxes would become inputs in quantitative climatology and extended-period forecasting. In the event, appropriate formulations were available by (in fact before) the time that the numerical models were sufficiently developed to incorporate them.

Nor did Australians come 'cold' to the major numerical modelling tasks which confronted them as soon as CMRC was formed. Dr U. Radok and Dr M.J.D. Jenssen of the University of Melbourne had initially addressed the numerical forecast problem in the late 1950's. Mr R. Maine and Mr G. Rutherford had made progress during the mid 1960's with the development of numerical analysis and prediction in the Bureau, later to be joined by Dr D.J. Gauntlett and Mr R.S. Seaman. Dr R.H. Clarke of CSIRO, while at the Geophysical Fluid Dynamics Laboratory (GFDL) in the U.S.A. had made the first baroclinic numerical prediction for the southern hemisphere. Mr B.G. Hunt, also at GFDL was involved in the rapidly developing field of numerical general circulation and climate simulation. Subsequently he and Dr W.P. Bourke were recruited to CSIRO for numerical studies of the general circulation.

Throughout the preliminary thinking and negotiations as recounted above a number of things had been constantly in mind: 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; that a straight takeover or simple adaptation of techniques developed in the northern hemisphere would not be good enough; that the immense and predominantly oceanic data gaps, and the scientific difficulty which these imposed, would throw up a host of new problems; that it would be many years before researchers in the northern hemisphere could afford to engage these southern problems; and that no other southern country would be capable of mounting the requisite effort. Thus Australia stood not only to help itself, but to make a signal contribution of hemispheric and world benefit.

At this, the time of the Centre's disbandment, its past and present members will look back with pride at the results achieved and with appreciative memories of collaboration with scientists outside, both here and overseas. We fully share their feelings, and in the context of this chapter bring forward one special name. Professor Joseph Smagorinsky (GFDL) gave unsparingly to us of his advice and wisdom in the build-up stages: in so doing, and in the collaboration successively with Hunt, Clarke, Gauntlett and Hincksman, and subsequently Bourke and Puri, GFDL made a lasting contribution to the development of numerical meteorology in Australia.

II. PROFILE OF CMRC/ ANMRC

The next four sections are contributed by Officers-in-Charge of the Centre, their terms of office indicated.

FORMATIVE YEARS — 1969–1973

G.B. TUCKER

The formation of CMRC in April 1969 occurred at an early and exciting stage of development in the international Global Atmospheric Research Programme (GARP). GARP, a joint program of the International Commission of Scientific Unions (ICSU) and the World Meteorological Organization (WMO), had two clear scientific objectives: to study the transient behaviour of the atmosphere with a view to increasing the accuracy of forecasting; and to study the statistical properties of the general circulation with a view to a better understanding of the physical basis of climate. It was natural therefore for a newly developing numerical modelling research group to be influenced by this international program and later to feed back its own influence. Indeed the propinquity between GARP and the burgeoning CMRC program was particularly appropriate because both involved a collaborative effort between research scientists and national weather service practitioners.

A few years earlier an interdepartmental review (Tucker and Moran, 1967) had outlined weaknesses in Australian meteorological research. The aim of CMRC was to focus on the most glaring deficiency: the urgent need for an up-to-date numerical modelling facility to be applied to both the synoptic scale problem of weather analysis and prediction and the larger scale problem of understanding the (southern hemisphere) general circulation of the atmosphere. A major task was the development of numerical models which would make good use of the new computer system recently acquired by the Bureau of Meteorology and also the computing power available in CSIRO. But it was recognised from the beginning that CMRC must have a two-fold objective: to develop an operational system of numerical analysis and prognosis of synoptic systems which could be adopted by the Bureau of Meteorology to perform its primary function of providing an information, forecast and warning weather service; and to carry out numerical experiments to study atmospheric behaviour and so to link with the research programs in the CSIRO Division of Meteorological (later Atmospheric) Physics where the primary function was to advance meteorological science.

New positions were provided by the Public Service Board to the Bureau of Meteorology to establish its component of CMRC. This enabled a small complement of half a dozen or so experienced meteorologists and programmers as well as some less experienced staff to transfer from the Bureau to CMRC. Similarly, positions from CSIRO enabled the early recruitment of four research scientists, all but one of whom had no previous experience in atmospheric studies. Thus, while a small nucleus of experience existed, to a large extent the early period of CMRC involved building up both a research program and competent scientific staff from very small beginnings. Careful judgement was required to assess whether the previous experience and meteorological interests of applicants to join the Centre were likely to yield progressive research achievements. This was particularly true for CSIRO research scientists new to the subject.

At the same time a lot of groundwork had to be done to establish the existence of CMRC in the national and international scientific scene. In these early years the Centre was, fortunately, not involved in institutional politics, possibly because it had not yet established itself and no-one knew whether it would turn into an asset or a liability. Within a few years of its formation, however, it became obvious that remarkable progress was being made. This progress was made known not only by research publications with their time lag of a year or so but also by a policy of encouraging short term visitors, both national and international. Indeed within a few years several of the principal scientists involved in numerical modelling had visited CMRC, including F.G. Shuman (NMC, Washington) and G.A. Corby (UK Meteorological Office).

Gradually more positions and staff were acquired until by March 1973, some four years after CMRC's formation, staff numbers reached 36, of which the 26 professional complement comprised 10 research scientists, 9 meteorologists, 6 programmers and a scientific services officer.

If these first four years can be regarded as 'the formative period', it is interesting to note the program and philosophy that had been developed and the achievements attained during this time.

From the beginning the importance of rapidly developing and implementing an operational numerical weather prediction system for the Bureau was recognised. This together with the twin GARP objectives provided the early research program sub-divisions:

- research application — the development of an operational system which could be taken over by the Bureau.
- analysis and prognosis — the development of improved numerical analysis methods, using conventional and new (satellite) derived observations, and of improved numerical weather prediction models.

- general circulation studies — the performance of numerical geophysical experiments and observational studies of the southern hemisphere general circulation.

Notwithstanding understandable Bureau requirements for a variety of operational systems to be developed as soon as possible, the autonomy of CMRC and its organizational separation from the Bureau allowed staff to develop individual skills and potentialities to the full — aided in no small measure by association with CSIRO research philosophies. This separateness also allowed the proper development and testing of numerical models without the inevitable service pressures of a national weather service forcing "an inadequate basic framework into premature servitude" (Smagorinsky, 1970). In fact, a rather unique balance was achieved between research freedom from service requirements. This balance soon became internationally admired and, even in these formative years, led to remarkably rapid achievements.

Some of these achievements were closely related to contiguous developments overseas. Indeed, the early analysis and prognosis schemes cannot fairly be described other than as reflections or southern hemisphere adaptations of northern hemisphere developments. However the difficulties of the data-void southern hemisphere presented a major new challenge. Application of these methods to the Australian scene was enhanced by strong international cooperation and in particular by the interest and unstinting help provided by the Geophysical Fluid Dynamics Laboratory at Princeton, N.J., a component of the U.S. National Oceanic and Atmospheric Administration (NOAA). This led to what is perhaps the most outstanding practical achievement of CMRC. R.S. Seaman and D.J. Gauntlett became the principal architects of a numerical analysis and prognosis system for the southern hemisphere, a system which successfully overcame for the first time the data problem. Indeed this represents a landmark in Australian meteorology as evidenced by the wide operational usage of numerical analyses and prognoses for the southern hemisphere from this period onwards. Thus, even in its formative years, strong international associations fostered as a matter of policy within CMRC paid off handsomely.

Other achievements however, while generally aided by international collaboration, were clearly the result of insight and industry by one or more individuals at the Centre. Of the several examples which might be cited the following four are particularly worthy of mention.

Within the first year of the Centre's formation one scientist (W.P. Bourke) began to consider the formulation of an atmospheric model via the spherical harmonic representation of the dynamic variables. He later spent some time at McGill University and in the Research Group of the Canadian Weather Service developing this model and studying associated spectral transform methods. By March 1973 several experiments with a hemispheric baroclinic model had been carried out, with results which had important implications for forecasting using spectral models. Subsequently, as a result of this pioneering effort, the Australian Bureau of Meteorology was the first organization in the world to adopt a spectral forecasting model for routine operations. The spectral model formulation developed in CMRC is now used by many of the major research and operational centres overseas, for both weather and climate study purposes.

Since the early 1960's cloud patterns derived from satellite had been used effectively by Australian meteorologists as an aid in locating frontal zones and low pressure centres over the observation-sparse southern oceans. When CMRC began developing numerical analysis methods for application over the southern hemisphere it became obvious rapidly that a much more comprehensive and quantitative use of these cloud patterns was necessary. Indeed they were the only way at that time in which conventional land-based and ship-based meteorological observations could be adequately supplemented to provide meaningful numerical analyses of the entire southern hemisphere. A scientist from the CSIRO Division of Atmospheric Physics (the late A.J. Troup) was seconded to the Centre to work with N.A. Streten. Together they developed a classification of cloud signatures for different stages in the development of atmospheric vortices. This enabled surface pressure and upper geopotential anomaly patterns to be allocated quantitatively to areas of the map occupied by particular cloud patterns. This work together with that undertaken by forecasters at the Bureau Central Analysis Section, in particular that of L. Guymer, has led to a method of deriving 'bogus observations' from satellite derived cloud patterns; such observations are still an essential input to southern hemisphere analyses undertaken not only in Australia but also in the major northern hemisphere global analysis centres.

By 1973 a more quantitative application of satellite derived information was being undertaken (by G.A. Kelly) at the Centre. Downward looking radiometers providing measurements in eight different infrared channels were now being flown on satellites and, beginning in January 1973, temperature profiles obtained by reduction of these data were sent to CMRC from the United States National Environment Satellite Service. The potential of these new observations, which amounted to some 400 soundings over the southern hemisphere every twelve hours, was enormous. It was obvious at this early stage, however, that for many situations the radiance reduction techniques were inadequate and experiments were commenced aimed at improvements. Such improvements developed at the Centre, and closely interwoven with numerical analysis and prognosis schemes, are now in routine operation at the Bureau of Meteorology.

The first stage of yet another innovation in numerical weather prediction was also completed during the formative years. In 1972, under the guidance of CMRC scientists, a visitor from the New Zealand Meteorological Service (D.K. Purnell) undertook some work on a regional version of a primitive equation forecasting model and produced a number of 24 hour forecasts for the Australian region. In later years work in this area blossomed and fine mesh regional models are now part of the armoury of the Australian Bureau of Meteorology. This example represents the first of a series of long term visits by overseas scientists some of which have led to the establishment of mutually profitably links. Such visitors together with similar visits to major northern hemisphere establishments by CMRC scientists who had acquired an international reputation helped establish the Centre as a major research institute on the world scene.

In addition to these achievements which led immediately and subsequently to improved analysis and forecasting capabilities at the Bureau, several geophysical experiments aimed at a more fundamental understanding of atmospheric processes were already being carried out. These included a synthesis of southern hemisphere atmospheric developments over 122 days via a general circulation model and the detailed examination of a model generated storm. Also undertaken were studies of the response of grid point hemispheric models to a low latitude sea surface temperature anomaly (in the days before this topic became fashionable) and to the simulated insertion of volcanic debris in the stratosphere and consequent modification of shortwave radiation. Given the long lead time required to develop and test general circulation models the successful performance of these early experiments was quite remarkable, and much credit must go to B.G. Hunt. Associated with these general circulation simulation experiments, observational studies were also necessary to allow comparison of the performance of models with the observed atmosphere. These included wave number spectra of travelling and stationary waves and the identification of synoptic developments in both tropics and mid latitudes as revealed by satellite cloud observations.

Thus within four years of its formation a clear course was set at CMRC, in terms of a research program which combined the development of operational numerical weather prediction systems with research into improved analysis and prognosis methods, and combined geophysical experiments using general circulation models with diagnostic studies of the observed atmosphere. But more important was the establishment of a philosophy which encouraged focused research and the development of specialised skills rather than attempting to cover too wide a field less deeply. An essential element in this philosophy was the value placed on research publications in the highest rating international journals. This ensured critical scrutiny via pre-publication refereeing procedures and the widest dissemination of results. Also, by establishing international reputations, it assisted progressive research by mutual interaction of scientists in the international scene and constructive criticism amongst those leading the field. Such publications were also an overt record of achievement.

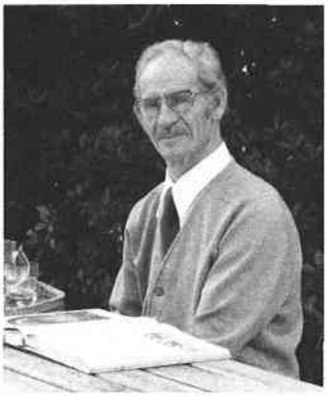
In summary, a feature of the formative years of CMRC was the rapid attainment of a very creditable research output while at the same time providing over a remarkably short period the beginnings of a high quality operational numerical analysis and prognosis system.

References

SMAGORINSKY, J. (1970). Numerical simulation of the global atmosphere. In: **The Global Circulation of the Atmosphere** (G.A. Corby, ed.) Roy. Meteor. Soc., London: 24–41.

TUCKER, G.B. and P.V. Moran (1967). Report on a proposed meteorological research programme. Unpublished report, Australian Bureau of Meteorology and Australian Public Service Board, 57pp.

ANMRC 1974–1977



R.H. CLARKE

Following the 1973 Review of the Commonwealth Meteorology Research Centre (CMRC), both its name and its management structure were changed. The most important change was that the Centre, now called the Australian Numerical Meteorology Research Centre (ANMRC), became an independent unit, with the Officer-in-Charge (OIC) jointly responsible to the Chairman of CSIRO and the Secretary, Department of Science. As the Centre was classed as one of the four CSIRO member laboratories of the Environmental Physics Research Laboratories (EPRL), the OIC was also answerable to its Chairman, Dr C.H.B. Priestley, who was a source of strength in troubled times. He, in turn, was one of the Centre's four-man Advisory Committee on Policy and Programs. The other three were the Director of Meteorology (Dr W.J. Gibbs); the Chief, Division of Atmospheric Physics, CSIRO (Dr G.B. Tucker); and Mr J.P. Lonergan, First Assistant Secretary of the Department of Science, who was a good ally of ANMRC.

It appeared to the newly appointed OIC, at the end of 1974, that ANMRC was a centre of excellence in a very difficult environment, and that all possible steps should be taken to gain for it proper recognition of the important work it was doing, both nationally and internationally. Especially was it important to 'sell' itself to the Bureau of Meteorology, as a provider of expert analytical and prognostic tools for the Bureau's National Meteorological Analysis Centre (NMAC). This was a difficult task, partly because ANMRC was seen by many as an 'ivory tower', more concerned with pursuing scientific and academic prestige than with the main task for which it was created: "the development and application of numerical models directed towards improvement in the accuracy and time scale of weather forecasting, and towards improvement in understanding the distribution and variations in climate on earth."

It was believed that action on two fronts could be taken to improve ANMRC's 'image' in the Bureau. One was to use the Advisory Committee as a medium to convince the Director and the Department of Science of the Centre's *bona fide* desire to complement the Bureau's work in every way possible, and to adopt a 'low personal profile' in a bid to relax the stultifying tensions of the past. The other was to attempt to bring about better communication and interaction at the working level in the two organizations.

One of the first actions of the new OIC was to approach the Director, an old and valued friend, with a suggestion for the setting up of a joint Bureau-ANMRC committee to actively pursue the goals of improving relations at the working level and facilitating the adoption of ANMRC research products in the Bureau. Such a joint group was set up early in 1975, under the name Joint Working Party, which was to meet monthly and report progress to the Director and OIC. Over the next several years this Working Party was to contribute considerably to communication between the Bureau and ANMRC, and to smooth the way for the acceptance of ANMRC research products. One result has been that between 1976 and 1983 the skill score (normalised mean error in operational prognosticated 24 hour surface weather maps) has declined steadily from about 51 to 42. The 1970–1975 mean error for 'manual' prognostics (made with benefit of the numerical prognostic) was 49. This result indicates that ANMRC and NMAC in partnership have evolved one of the best predictive systems in the world, in a uniquely difficult geographical area.

The improvement in predictive skill is attributed to a new method of objective analysis; to greatly improved methods of using satellite radiometer data; to the adoption of radically new prognostic models and methods of initialization; and to the marrying of the Australian regional model to the hemispheric spectral model. It has been a significant achievement; the benefits are still accruing, in the form of a continuing downward trend in the errors, and higher spatial resolution in the predicted fields. One feels that this success justifies the optimism of the 1970's. It also supports the stand taken by the authors* of the "Report of the Independent Inquiry into the Commonwealth Scientific and Industrial Research Organization", published in August 1977: "The Australian Numerical Meteorology Research Centre . . . forms a bridge at present between the Bureau and CSIRO . . . We suggest that this model is a good one . . ." The implication was that ANMRC was fulfilling an important role, judged by the Inquiry's standard: "While the initial objective of research is to obtain new knowledge, the ultimate objective is to see that this knowledge is usefully applied."

From December 1976 to September 1977 the reports from three reviews affecting ANMRC were released.

The first, and most painful for ANMRC, was a "Report of the Committee of Inquiry into the Bureau of Meteorology", dated December 1976**. This report showed that the attempts being made to refurbish the 'image' of ANMRC in the Bureau had **not** borne fruit. On the contrary, the Bureau appeared to have persuaded the Inquiry Committee that it was not receiving "benefits from the Centre commensurate with cost", which was surprising in view of the superior Centre products being used in the Bureau at that time, especially the 36 hour

* A.J. Birch, C.T. Looker, R.T. Madigan

** By P.W. Howson, J.L. Farrands (Secretary, Department of Science), W.J. Vines.

hemispheric spectral prediction model and the variational blending analysis scheme. Even more surprising was the implication that the benefit of continuing research into numerical weather prediction (NWP) was in doubt: ". . . the Bureau should concentrate its research effort in-house . . . and include research into numerical weather prediction **if this still seems promising at the time**." (My emphasis.)

The last statement suggested strongly that the Committee and those in the Bureau who had advised it should be persuaded to face the fact that weather forecasting was most unlikely to improve in quality except through a proper scientific approach, involving the solution of numerous partial differential equations, effectively, through the numerical approach. Many years of extrapolating features on maps, i.e., the empirical approach, had proved sterile in this regard. The OIC of ANMRC was moved to drive home these points by delivering a lecture in the Bureau and writing a monograph (1977) "The future of weather forecasting in Australia". There are indications that the basic philosophy expressed therein has, since then, been generally accepted in the Bureau.

The Howson Committee concluded: "Somewhat reluctantly . . . we have accepted that the Bureau should continue to participate in the ANMRC", but "at the end of the current agreement . . . the Bureau should concentrate its effort in-house . . ." This was little less than the death-knell of a centre of excellence at the height of its creativity, a severe morale-destroying blow from which recovery was hardly possible.

The shattering blow delivered by the Howson Committee was somewhat mitigated by the next two reviews: the Inquiry into CSIRO by the Birch Committee in August 1977, mentioned above, and the Review of EPRL (September 1977) chaired by Dr H.W. Worner*. The Worner Committee gave ANMRC its seal of approval: ". . . ANMRC as an independent unit operated jointly by CSIRO and the Bureau of Meteorology [*sic*]** is a unique arrangement, which has proved very successful in ensuring close cooperation by the active participation of both Organizations in the formulation and implementation of research programs. Many of the Centre's research findings have already been incorporated into the Bureau's operations or await implementation in the Bureau and both bodies receive additional benefit from this close interaction of research and operational staff." The recommendation to the CSIRO Executive was that it should "negotiate to renew it [the enabling agreement with the Department of Science] for an indefinite term", and that the OIC should "remain responsible for the direction of the research program and will not be subject to any direction by the Advisory Committee on Policy and Programs." A sour note in this review was the statement that "collaboration with other CSIRO Divisions has been somewhat limited" and "**the Committee recommends** that this be improved." This was a complaint commonly heard from the Division of Atmospheric Physics, and continued, despite successful efforts to persuade staff to attend seminars as widely as possible. The fact of the uniqueness in Australia of many of ANMRC's interests and problems, and the

* Other members were N.K. Boardman, J.P. Wild, N.H. Fletcher, B.R. Morton

** "Bureau of Meteorology" should have read "Department of Science"

30 km separating the two institutions, accounted for the appearance of insularity in ANMRC, but there was certainly none on the international scale (nor in relations with the Bureau); most of the staff had worked in overseas institutions at some time, and had international contacts.

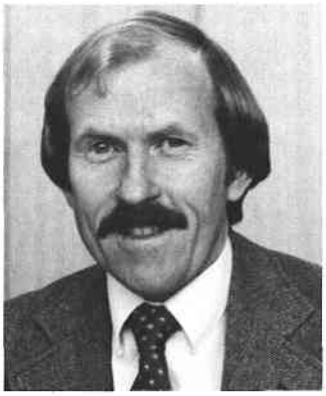
The Centre had only one more review to undergo. In 1982 the Philip Committee delivered the *coup de grace*, a recommendation, accepted by the Executive, with the words: "The current involvement of CSIRO scientists in numerical weather prediction directed to operational forecasting should cease on the disbandment of ANMRC" which, it was agreed, "should begin immediately".

Through this maelstrom of reviews and sometimes ill-informed and irresponsible criticisms, the dedicated research of ANMRC continued with little noticeable diminution of zeal. The Worner Committee was "**impressed with** the enthusiasm of the [Centre's] research staff from both CSIRO and the Bureau".

A constantly recurring problem during 1976–77 was insufficient computing power, measured both in terms of the capacity and speed of available computers and of the funds available to buy computing time. Time on the Bureau's relatively primitive IBM machines was not subject to specific charges, and the Centre was able to use time surplus to the Bureau's needs. (These, however, increased as time passed.) A lump sum for computer use was in fact debited against the Centre in the Bureau's budget, and this constituted a considerable portion of the Centre's running costs, whose magnitude the Howson Committee implied was not commensurate with benefits obtained. Costs for time on the far superior CSIRO computer had to be allocated from available funds. It was felt that, while CSIRO paid lip service to the notion of supporting the Centre as a bridge between the two organizations, it carried a disproportionately small share of the burden. Since the supply of computing power was never more than barely enough to meet the Centre's legitimate demand, and in 1977 fell somewhat below it, the OIC felt it was necessary to take urgent action to obtain relief. A case for a recurring extra $50,000 p.a. for climate research, to be devoted to studying the causes of drought in Australia, was taken to the Executive and met a positive response, and this helped to ease the rationing in computer use. At the same time, the Worner Committee was recommending that the Executive "provide additional computer time from CSIRO funds", and that "the [CSIRO] computer operate three shifts and that a special rate be charged for non-priority work".

One final aspect of the Centre's work deserves comment. While on one hand its scientists were being accused of living in an 'ivory tower', on the other, some of them were being subjected to increasing pressure to produce practical results, in the form of systems to demonstrably improve weather analysis and forecasting, and to produce them quickly. While there can be no doubt that this was a very worthy activity, it did not necessarily produce many published research papers. Since CSIRO scientists in particular achieve professional promotion through the quality and number of their published works, there may well be some in ANMRC whose careers have been detrimentally affected by their work situations. If such people received less than their proper share of promotion recognition for their devotion to the improvement of weather forecasting, this can only be regretted.

ANMRC 1978–1983



D.J. GAUNTLETT

Despite the uncertainty and disruption associated with both frequent reviews and the continuing administrative conflict over the Centre's role and functions, the latter years of the Centre's existence were paradoxically the most productive. In part, this was due to the excellent scientific foundations established by previous Officers-in-Charge. However, there was also a major scientific stimulus and this was the opportunity provided in the form of the extra observational data which ensued from the GARP Global Weather Experiment (GWE). For the first time the southern hemisphere was observed to an accuracy approaching the requirements of contemporary numerical models and for the scientists involved, this was an opportunity not to let pass by.

In order to take advantage of the GWE data, two major initiatives were developed. The first involved the construction of an advanced four dimensional data assimilation model using the highly successful ANMRC spectral model as the predictive component of the assimilation scheme. Several substantial technical problems were addressed and solved, not the least of which were maximizing the information impact of 'single level' data such as those provided by the extensive ocean buoy network, and the associated issues of numerical stability and efficiency. The development of a local expertise in the now well established field of normal mode initialization was an important additional step towards solving these problems. As a result of these research endeavours it was demonstrated that the practical limits of predictability in the southern hemisphere could be extended to at least three days — a limit that operational prognoses from the European Centre for Medium Range Weather Forecasts now routinely exceeds.

In parallel with these developments a major thrust was also made on the applicaton of the GWE data in short range forecasting using a higher resolution Australian region primitive equation (ARPE) model. By this stage the ARPE model had already demonstrated its superiority over previous numerical models developed for the National Meteorological Analysis Centre (NMAC) of the Bureau. The challenge at hand was to improve on this performance by maximizing the impact of the GWE data through redevelopment of the model (principally the provision of time dependent lateral boundary conditions) and the introduction of appropriate data assimilation procedures. Again these initiatives were successful and further gains in prognosis performance were achieved.

The success of these experiments and developments led in turn to an increasing optimism that we could proceed beyond the restricted synoptic scale application in the southern hemisphere of deterministic forecasting models to include a genuine consideration of the mesoscale. Two initiatives were again necessary to test this hypothesis. The first involved the development of a capacity to generate initial data at densities approaching the mesoscale. It was decided to promote a local capacity for the direct readout of high resolution sounding data from the TIROS–N polar orbiting satellites and to develop the requisite software to enable production of high density temperature profile information. These initiatives were greatly facilitated by drawing on the technical expertise developed previously in respect of Vertical Temperature Profile Radiometer (VTPR) sounding application in the northern hemisphere and a very close working relationship with the Space Science and Engineering Centre of the University of Wisconsin. The TIROS–N data were then used in conjunction with a new movable fine mesh (MFM) mesoscale prediction model in an attempt to forecast troublesome local small scale phenomena such as the development and translation of mesoscale cold pools and 'Southerly Busters'. Early results from these continuing experiments indicate great practical potential.

In addition to the GWE there were other GARP experiments which had an important influence on the Centre's research activities. The Winter Monsoon Experiment (WMONEX) for example, resulted in a major involvement by the Centre in the development of a specialised tropical analysis and diagnostic capacity for the Australian region. Previously such initiatives had been hampered by inadequate data. However, this situation was largely redressed during WMONEX, enabling the development of both the appropriate modelling techniques and, most importantly, the confidence of the operational tropical meteorologists in the practical advantages of such methods.

Substantial progress was also achieved during this period in the Centre's climate research activities. Because of the inherent difficulty of climate simulation and diagnosis, it was inevitable that much of the Centre's early work in this field was concerned with developing a local technical capacity and 'feel' for the problems involved. By the late 1970's however, a much sharper focus had emerged occasioned in no small part by the increasing statistical evidence collated by ANMRC to link sea surface temperature anomalies, tropical anomalies in particular, with seasonal variations in regional rainfall. In order to investigate such linkages further the Centre embarked on a deliberate long term policy of enhancing its air-sea interaction modelling capacity with a view to developing a comprehensive ocean atmosphere general circulation modelling capability. Unfortunately the time constant of such developments was not compatible with changing local political and administrative circumstances and there is now a grave risk that the considerable investment made in this field will be dissipated with only a small fraction of the return that could have been realised.

An important 'spin off' from the air-sea interaction research initiatives was the development of a limited area modelling capacity for the Bass Strait region. Initially this research was instigated as part of a cooperative venture within the Victorian Institute of Marine Sciences (VIMS) and in the first instance consisted of the development of a simple depth averaged barotropic model for the region. Later, because of the considerable user interest generated by the project and the identification of several unique properties of the Strait circulation, this model was extended to include baroclinic processes.

Much more could be said about the detailed achievements of the Centre, not only during the period 1978–83 but also prior to this. However, the issue which probably really matters now is to ask the questions, "Why was the Centre a success?", and "How can this experience be translated into effective future research arrangements for the individuals and organizations concerned?". In my view, there were several reasons for the Centre's success. First, and perhaps most importantly, its research objectives were clear and well defined. Secondly, its resource base was broadly consistent with these objectives although inadequate computational facilities were a notable exception in this regard. Thirdly, it was single-minded in its pursuit of quality, especially when important decisions regarding research priorities and staff appointments were involved. A fairly high percentage of term appointment positions, for example, was always a feature of the Centre's management strategy, resulting in a healthy competitive scientific working environment. Fourthly, in an organizational sense, the Centre occupied a unique position in the applications/research spectrum. By effectively straddling the middle ground of this spectrum the Centre was not only aware of real life problems, but was also in a position actually to do something about solving them.

The translation of these characteristics into a new *modus operandi* for Australian atmospheric science research, and that component more directly associated with the development of future operational systems, will be no easy task. Already the concept of the new Bureau of Meteorology Research Centre is well advanced and it is to be hoped that the ANMRC experience will have a major influence in determining its goals and operating philosophy.

ANMRC 1983–1984

W.P. BOURKE

In early 1983 the timing of the foreshadowed disbandment of ANMRC was unclear; in November 1983 the target date was set at June 30 of the following year; in mid 1984 the target date was set at December 1984. ANMRC has thus passed its final years amidst some uncertainty. In the CSIRO context several resignations occurred in 1983, and several promotions of Meteorologists and Computer Systems Officers from ANMRC to the Bureau could only be met by acting promotions and appointments to and within ANMRC. These problems were of course compounded by the inability to recruit staff to the vacant CSIRO positions. So one may ask: How did we manage in these final years? In the following I have attempted to chronicle major activities and achievements in 1983 and 1984. In summary I believe ANMRC has, despite the cited organizational difficulties, continued with notable achievement.

A major task facing ANMRC during the past two years has been to expand on and implement the research developments of the years 1977–1982 on the upgraded Bureau computing facilities. Much of the ANMRC research in the late 1970's and early 1980's was conducted on the CSIRONET CDC 7600 computer. With the installation of the FACOM M200 in mid 1982 the Bureau acquired computing capacity which was equivalent in processing speed to that long available on CSIRONET. This new computing facility however, has provided ANMRC staff with an order of magnitude increase in effective computing facilities through the excellent access provided by the Bureau.

Some highlights of recent progress are summarised below:

Weather Research

- An objective tropical analysis system has been implemented on a quasi-real time basis. The system is now run twice per day following successful operational trials in April 1983 and final acceptance in the Darwin Regional Office where the scheme has been run since November 1983.

- A hemispheric assimilation and prediction system has been implemented in operational trials in the months of July and September 1983, and January and June 1984. This state of the art system represents the first major upgrade to the operational hemispheric analysis since 1971 and to the operational hemispheric forecast model since 1976, and has been handed to Operations in final form in July 1984.
- Development of a generalized prediction verification system.
- The Limited Area Regional Prediction Model has now been reorganized into a very general form with a range of resolutions in the horizontal and vertical, and with enhanced physical parameterizations. Operational implementation is in progress at the time of writing.
- Polar orbiting satellite microwave temperature retrievals have been applied successfully to the location of the eyes of tropical cyclones.

Climate Research

- A 10 year integration by a global climate model designed to study interannual variability has been completed.
- A coupled atmosphere-ocean model using the two-level global model and a mixed-layer model of the ocean has been developed and is being tested.
- Detailed analysis has been made of the middle atmosphere simulation generated by the global 54-level model with emphasis on the role of internal gravity waves.
- The ANMRC global spectral climate and prediction model has been implemented on the CYBER 205 computer recently available on CSIRONET.

Observational and Diagnostic Studies

- Analysis and interpretation of the El Nino/Southern Oscillation phenomenon have provided further evidence for the key role of air-sea interaction in the oceans adjacent to northern Australia. Seasonal tropical cyclone activity has been identified as strongly correlated with north Australian sea surface temperature just prior to the onset of the cyclone season.
- North Australian sea surface temperatures have been identified as a precursor to variation in intensity of the Indian summer monsoon rainfall.
- A comprehensive southern hemisphere climatology has been established and the standing waves in this climatology analysed.

- A crucial factor in the development of outbreaks of tropical convection and the genesis of intense monsoon depressions over tropical Australia has been investigated, namely the day to day variation in the southern hemisphere subtropical ridge.

As the sun sets on this relatively young research centre the momentum of valuable research has been essentially maintained. This is a particular tribute to those staff who, although faced with organizational uncertainty, have had the conviction that the quality of this research was sufficient to survive foreshadowed changes.

The Centre was conceived as a compromise solution to an organizational problem of the 1960's; it is being disbanded seemingly as a compromise now to solve problems of others. It could be said that its conception was scientifically more responsible than its disbandment. There can be no guarantee of continued success comparable to that provided by CMRC and ANMRC. This experiment in organizational structure generated an unexpected but superb result; analysis of the experiment has been available but not widely comprehended.

III. PERCEPTION OF A JOINT UNIT

J.P. LONERGAN, OBE BA MSc

Principal Scientist, RAN Experimental Laboratory Sydney, 1958–1965; Director of Scientific Services, Department of the Navy Canberra, 1965–1969; Superintending Scientist, Department of Defence 1969–1972; First Assistant Secretary, Department of Science 1972–1979. Deputy Secretary Department of Science and Technology 1979–1981. Chairman ANMRC Advisory Committee 1974–1979.

The ANMRC served a unique role in Australian science, and its programs without exception were aimed at results that would have application to community needs. It was outstandingly successful in its field, and at modest cost. Why then was it unceremoniously and incongruously abolished? It seems to me that thoughtful persons who, in particular, have some concern for the future of meteorological research in Australia, or who, more generally, have an interest in how important decisions are sometimes made here, would do well to ponder this question. It is from one perspective, that of Chairman of ANMRC Advisory Committee, that I offer the following comments on the matter.

There are, however, a couple of points that I think sufficiently important to warrant special mention at the outset. In the first place, when one looks back and recalls the administrative turbulence that, throughout the Centre's life, was never far below the surface in the contiguous domains outside it, it is quite remarkable that it should have been so unruffled in its internal operation and so very productive in its output. This, I believe, is not something to be merely mentioned and then promptly forgotten. On the contrary, it calls for recognition and acknowledgement of dedication and commitment by a small group of people. I will mention particularly Dr C.H.B. Priestley for his faith in the Centre and his unwavering support of it, and Dr R.H. Clarke and Dr D.J. Gauntlett who as Officers-in-Charge fought tenaciously on the battleground outside, and, at the same time, provided calm and purposeful leadership in the arena within. To their lasting credit, the staff who could not have been unaware of the Centre's vulnerability never let this interfere with the task in hand and never reflected outside any attitude other than confidence in the program and in their ability to implement it successfully. They are to be commended for their dedication and their competence.

Secondly, I want to emphasise that, in speaking of the **success** of the Centre, I do not do so idly or as a result of a purely subjective assessment, for 'success' was a term that recurred and recurred in the professional judgements of those who made submissions to the review, to which I will refer later, and who were qualified to make scientific appraisals. Moreover, in enquiries that I made overseas as part of that review, I found that the work was of genuine international repute, and readily and generously acknowledged as such by the Heads of the UK Meteorological Office, the French Meteorological Service, and the European Centre for Medium Range Weather Forecasts. The compliments to ANMRC's results and to the scientists involved were intended by these distinguished officials to be taken as their professional assessments, and they were certainly not offered lightly.

My first acquaintance with the Centre came shortly after the Bureau of Meteorology was attached to the newly created Department of Science, and it soon became apparent that there were serious disagreements within the then Committee of Management. A new agreement between CSIRO and the Department for the operation of the Centre came into force in August 1974 and I found myself appointed Chairman of a newly constituted Advisory Committee reporting to the Secretary of the Department and the Chairman of CSIRO as the joint principals. The Advisory Committee's main tasks were to review the program of the Centre, to recommend on future work and to comment on the proposed budget. Apart from the intractable and persistent difficulties posed by resource constraints, other problems of an administrative or procedural nature were soon resolved and improved interfacing arrangements between the Centre and the Bureau were put into effect.

The Advisory Committee, as a corporate body, came to work very well indeed, and it is a pleasure to place on record my appreciation of the cooperation I received from all members during the six years or so that I was associated with it. The members were Dr Priestley, Dr Tucker, Dr Gibbs and, after the retirement of the last-named, Dr Zillman. The Officer-in-Charge of the Centre participated fully in the meetings of the Committee, to the advantage of all concerned. It is to the credit of the Director of Meteorology and the Chief of the Division of Atmospheric Physics that, whilst they each had very firm ideas on what would constitute in their respective views better alternative arrangements for the conduct of meteorological research in Australia, nevertheless their participation in the business of the Advisory Committee was always wholehearted, constructive and fruitful. Out of Committee, however, they were fully entitled to canvass their own ideas, and I believe that, in part at least, the seeds for the Centre's eventual demise stemmed from this circumstance, albeit indirectly.

From the earliest days of the Department of Science through until the retirement of its First Secretary, departmental support for the Centre was based on the following reasoning. There existed a very real, and indeed urgent, need to conduct meteorological research in Australia of the highest practicable quality, with the aim of improving the accuracy and scope of weather forecasts. For the foreseeable future, at least, the way ahead seemed to lie in numerical modelling. The Centre had already developed a great deal of competence in this area, the scale of its efforts was pitched at a realistic level, some of its products had gone into service, and its then current program offered the substantial promise of providing new forecasting methods that could be adopted with advantage by the Bureau. We were convinced that a 'research scientist' based effort was mandatory, and, equally, that we had no prospects of obtaining Public Service Board approval for the requisite organizational structure within the Bureau. There was another important consideration. When any organization that includes a research facility is hard pressed, it is invariably the research program that is the most vulnerable to crisis situations, and, typically, the pursuit of research becomes subservient to pressing operational demands and secondary to the maintenance of services when resources are cut. The joint undertaking by the Department and CSIRO to sponsor the Centre at an agreed resource level provided a reasonable assurance that the research would be insulated to a large degree from such a possibility, and it also overcame the problem of employment of research scientists.

Subsequently the arrangements worked well and the Principals abided by the terms of their commitments. The Centre for its part, despite the fact that in the event it suffered considerably from the resource constraints applied by the Government, lived up to expectations and achieved results that are detailed elsewhere in this report.

A major review of the Bureau of Meteorology by an independent committee of enquiry, 'The Howson Committee', was completed at about the end of 1976 and its outcome, I believe, gave the Director of Meteorology some cause to feel that research within the Bureau might subsequently be significantly strengthened. No doubt the hope thus engendered would co-exist uneasily with any long term commitment to the Centre. Meanwhile the Chief of the Division of Atmospheric Physics was coming to the view that the Centre was inexorably moving away from its limited charter and that the interests of meteorological research would be better served in the long haul if the Centre were disbanded and research programs were entrusted to the Bureau and the Division collaborating under some form of gentlemen's agreement. With this view the Director of Meteorology, I believe concurred.

Dr J.L. Farrands who had been a member of the Howson Committee was appointed Secretary of the Department of Science late in 1977, and his strong conviction was that the Bureau should strengthen its in-house research capability. Then, towards the end of 1978, the Chairman, CSIRO and the Secretary, Department of Science, appointed a committee to review ANMRC, comprising myself as Chairman, and Dr N.K. Boardman and Professor B.R. Morton as the other members. We received a large number of submissions, in writing and/or in personal presentations, and the outcome of our deliberations was to accept the considerable weight of scientific opinion endorsing the excellence and relevance of the Centre's work, and the recommendation strongly expressed by the majority of respondents that the Centre continue in its existing role.

Decisions on our recommendations had not been finalised by the Principals when the Committee of Review of Government Functions, chaired by Sir Phillip Lynch, came into existence with a mandate to identify ways of trimming the public sector. The Secretariat of that Committee, presumably getting wind of the controversy surrounding the Centre, took little time to point to it as a target for potential abolition. Neither CSIRO nor the Department took kindly to the idea that a decision about ANMRC's future should be made in this way — but that is how it finally turned out.

Those of us who can understand the issues involved — the scientific and organizational aspects, and the genuine aspirations of the people caught up in the affair, those who were pro-ANMRC and those who were anti — should all be saddened by the sorry way in which the Centre's future was decided. It says little for public administration in Australia when important decisions, as a decision about the future of the Centre certainly was, are taken on this sort of a basis.

Those of us who came to care about what the Centre stood for will now be looking to the Director of Meteorology and the Chief of the Division at Atmospheric Research to seize the opportunity now presented to them to give effect to the promise they made, that in collaboration they could do at least as good a job as the Centre. When the future work receives the measure of acclaim that the ANMRC's work did, we can all be content that the promise has been honoured.

IV. CMRC/ANMRC RESEARCH INTERACTIONS

INTERFACE BETWEEN CMRC/ANMRC AND THE BUREAU OF METEOROLOGY

P.F. NOAR, MSc

Joined the Bureau of Meteorology 1957; CMRC 1970–1975; Head of NMAC, Bureau of Meteorology 1975–1983, Assistant Director (Services) from 1983. Member of the ANMRC/Bureau of Meteorology Joint Working Party 1975–1983, Chairman from 1978.

This essay is written from the perspective of a former staff member of CMRC/ANMRC who was associated with research applications/operational interface activities from 1971–75, and who then became leader of the National Meteorological Analysis Centre (NMAC), the major Bureau user of ANMRC research. Major strengths of the Centre were the CSIRO type working environment, and its explicit objectives to advance operational numerical weather prediction (NWP) in the Bureau of Meteorology. It is difficult to assess what results would have been achieved had the Centre not been formed. Certainly a good start on NWP research had been made with the Numerical Methods Section of the Bureau's Research and Development Branch by people like R. Maine (now Assistant Director Computing), D. Gauntlett (later Officer-in-Charge of ANMRC, and now Deputy Director (Research and Systems)) and R. Seaman (now a very senior research meteorologist in the Centre) and later G. Kelly (also in the Centre). There would have been a progression towards the development and application of primitive equation models. However the group of CSIRO Research Scientists who formed a nucleus of the Weather Research Group have made contributions of international importance. The pioneering work on spectral models and initialization methods by W. Bourke, K. Puri and B. McAvaney, and the collaboration between D. Gauntlett and L. Leslie stand out as major contributions.

I joined the Centre as an experienced synoptician with a keen interest, but no experience in numerical weather prediction. My duties, after a long apprenticeship, included the testing of regional and hemispheric models, the conducting of trials, re-runs of specific situations, verification studies and experiments with pseudo-observations. In this work I acted collaboratively with J. Young, a senior programmer with a scientific flair, and an early project was the restructuring of the Maine filtered baroclinic model to test the contributions of secondary terms in the model equations and to optimize surface friction, topography and the correction to the vorticity equation to compensate for long wave retrogression. The Mark II version of the regional filtered model replaced the Maine model in 1972 and was used as the NMAC regional model until 1977. A hemispheric version developed by J. Young was run operationally until replaced by the Bourke spectral primitive equation model in January 1976.

A number of experiments was conducted by D. Gauntlett, W. Kininmonth and D. Hincksman during 1972 and 1973, testing the hemispheric primitive equation model on operational data and utilizing differing initialization techniques, improved representation of convection, and differing time integration schemes. At this stage the limitations in core and capacity of the IBM 360/65 for advanced numerical modelling became an acute problem. After optimization the grid primitive equation model took 90 minutes to execute a 24 hour forecast. The model showed significant skill in a number of significant weather situations, for example cut-off lows. The late D. Wright of the Bureau undertook an assessment of a series of 25 four day forecasts and found useful skill at the end of the forecast period in more than 50% of cases. Pseudo-observations prepared by operational analysts were, and still are, deemed to be essential over the southern oceans.

During this period the spectral primitive equation model was being developed by W. Bourke and his group. Despite difficulties in representing topography, and limitations in resolution, the spectral model was more efficient in computer usage than the grid model, and indications were that it was superior in performance to the filtered model. Eventually after tough negotiations with the late R. Falconer, leader of the NMAC Operations Development Section, operational trials were organized. At issue were several questions which were to assume importance in later years. The first of these was the method and extent of testing the performance of the model and comparing it with the operational model. Both objective and subjective tests were agreed upon, culminating in extensive parallel operational trials. The second question was the relative effort between the Centre and the Bureau in adapting the model to the real time system. In the event, more than 12 months' work was required to prepare the spectral model for operational use. The third question was the degree of documentation which would be required to facilitate provision of information to the Bureau on model and data set structure for the purpose of program maintenance. A further underlying issue was the adequacy of interface arrangements within ANMRC. Indeed NMAC and ANMRC had become convinced that rather than a small, non-specialised interface group, a more efficient arrangement would be for the developers of models destined for operational use, to liaise more directly with the Operations Development Section.

In early 1975 I took over from the late A. Muffatti as Superintendent of NMAC, at about the same time that R. Clarke, Officer-in-Charge of the Centre, and W. Gibbs, Director of Meteorology, were devising new more formal interface arrangements. The first meeting of a newly formed Joint Working Party (JWP) was held in April 1975 under the chairmanship of D. Gauntlett, and considerable attention was given to formalizing terms of reference and to refining a flow chart devised by J. Lonergan, Deputy Secretary of the Department of Science and Chairman of the ANMRC Advisory Committee, to define the various stages of a new project initiation, development and implementation. Apart from providing recommendations and information to the Advisory Committee, the JWP served as a useful forum for debate on a number of relevant scientific/operational issues, usually through the circulation of discussion papers. An early initiative was taken by R. Seaman to improve grid point wind prediction for aviation in the tropics and subtropics via analyses based on optimum interpolation in space and time and predictions from these analyses based upon statistically damped persistence.

Initial moves were made during 1975 to highlight user requirements for tropical numerical analyses with a view to initiating a research project within ANMRC. Seven years were to elapse before the Davidson/McAvaney tropical analysis was developed, due largely to other priorities, and partly one suspects, to the low profile at that stage of tropical meteorology. I believe that the operational availability of imagery from the Japanese geostationary satellites (GMS 1 and later GMS 2) from 1978 did a lot to raise our consciousness of the importance of tropical meteorology and tropical/mid latitude interactions. The availability of cloud vector winds on an operational basis from 1980 onwards had a very beneficial impact on Darwin's manual analyses and are seen as essential also to the objective analysis scheme.

Consultations were made with A. Powell, regional representative on the JWP (now Regional Director, Victoria), and Bureau Regional Offices on the question of tropical analysis and the requirements for research in general. The JWP at this stage felt that regional input was essential to specifying new projects and recommending priorities, but at the same time stirred up something of a hornet's nest in high places. It was seen to have a penchant for impinging on areas of responsibility other than its own. However the information received was valuable in planning changes in NMAC output and giving focus to the implementation of the Australian region primitive equation model.

Implementation of the spectral model was a significant event, since NMAC was the first operational centre in the world to have available a model of this type. However, being constrained by computing limitations to five levels in the vertical and rhomboidal wave number 15, the model from the outset suffered from systematic deficiencies, including unrealistic equatorward drift and loss of intensity of anticyclones, unrealistic treatment of cut-off lows and occasional drastic weakening of sub polar lows. These deficiencies seriously undermined the confidence of regional users. On the other hand the model formed an important input to manual Indian Ocean prognoses, provided essential boundary conditions to the nested Australian region primitive equation model, and provided essential guidance for Antarctic aviation forecasts. Despite the limitations under which it has had to operate the impact of the model must be judged as positive.

The harshest test of all is to predict the relatively small proportion of significant weather events which have the greatest community impact. At the instigation of the then Director, W. Gibbs, the JWP undertook a project in 1977 and 1978 to examine the skill of the regional model in predicting a number of significant weather parameters, including vorticity centres, cold pools, warm tongues, areas of convective instability and rainfall. Success in predicting most of these phenomena was assessed as being less than 50%, indicating the critical need for improved mesoscale data, analysis and prediction.

An archive of regional primitive equation prognoses was established in 1980 enabling development by Research and Development Branch staff (F. Woodcock, G. Mills, R. Tapp) of model output statistics for prediction of maximum and minimum temperature and precipitation.

During 1976 the Bureau/ANMRC Joint Working Party provided comment on the section of a Government Green Paper relating to numerical weather prediction. In particular there was considerable debate on the importance of observational networks and techniques versus adequate computer power. I had argued that the deficiencies in observations and techniques at this stage outweighed the need for additional computer power, however desirable this was seen to be. The FGGE drifting buoy program, ASDAR and TOVS were on the horizon, and by 1978 the JWP had come to the conclusion that lack of computing capacity was the major factor severely limiting the Bureau's ability to implement the improved models developed by ANMRC. The points made in the JWP paper, written largely by W. Bourke, remain equally valid in 1984 as they were in 1978. On the one hand there are obvious benefits and attractions in gaining access to a CRAY or CYBER 205 machine; on the other hand the large sum of money precluded the Bureau from taking this course.

At one stage in 1979, whilst I was Chairman of the JWP, I expressed both positive and negative views in a report to the Bureau's executive management. On the one hand I listed twelve valuable discussion papers which had been prepared and circulated, and outlined the manner in which requirements for research, and implementation of research had been specified and facilitated. On the other hand, in a fit of candour I wrote:

> "A major problem during the lifetime of the JWP has been the lack of a tangible response from its Principals to the recommendations or comments made . . . We have on occasions been frowned at or even growled at . . ., but I can find no evidence of suggestions e.g. on MOS or tropical analysis being actively supported by top management . . ."

On the question of the proposed computer upgrade, I wrote formally to the Director (J. Zillman) and Officer-in-Charge, ANMRC (D. Gauntlett) in March 1979:

> "The introduction of the JWP Report stated the reasons for its preparation and the concern felt by members that they have a responsibility to state a scientific rather than economic view on the Bureau's future computing requirements. The current restraints are very well known, but the case must be put that if we are to take advantage of improvements in data and techniques a very large upgrade will be necessary. The incremental benefits can be assessed as being very significant, but it is the task of government to decide whether the nation wishes to pay for such an upgrade.
>
> "Members of the Joint Working Party consider that the question is vital to both research and operational activities and on their behalf I wish to request a response from the Advisory Committee to the matters raised in the report."

There was considerable debate within the higher echelons of the Bureau during this period on how much of an upgrade of the central computers could be supported, but the Director replied courteously and positively, stating in part:

> "The JWP's assessment of, and comments on, the future computing needs of the Bureau represent one very important input to the Bureau Executive's consideration of the approach to be taken in framing a submission to Government for replacement/upgrading of the Bureau's central computers. I would like to thank you and the members of the JWP for the effort that went into preparation of the report and for the views expressed in it."

A number of heated debates occurred between Bureau and ANMRC staff members during 1981 on the strategy for converting analysis/prognosis programs to the new FACOM M200 computer. All the scientists and computer systems officers directly undertaking the work were and are highly dedicated. Operations Development staff implemented several practical models designed to assist forecasters directly (vorticity and vertical velocity maps, an empirical sea state prediction model, SAM PROG, SLYH rainfall prognosis, as well as considerable development/implementation of the TOVS local readout initiated by G. Kelly). The conclusion immediately prior to the disbandment of ANMRC is that in addition to the continuous day to day contact between individuals, the JWP performed an essential interface function in identifying problems, providing information both laterally and upward and in facilitating cooperative action. I would consider that one or more reasonably formally constituted interface committees should operate when the Bureau of Meteorology Research Centre (BMRC) is set up.

Output from numerical analyses and prognoses now forms a central component of the Bureau's Forecasting and Warning Program. Essential to the success of the numerical system has been both the research undertaken in ANMRC, and the operationally focused scientific and systems expertise in the Operations Development Section and ADP Real Time Support Group.

COLLABORATION BETWEEN THE CMRC/ANMRC AND THE METEOROLOGY DEPARTMENT OF THE UNIVERSITY OF MELBOURNE

W.F. BUDD, MSc PhD DipEd

Antarctic Division Expedition Glaciologist 1960–1966, Head of Antarctic Division Glaciology Section and Academic Associate of the Department of Meteorology University of Melbourne 1967 – 1979; Professor of Meteorology, University of Melbourne since 1979.

The Meteorology Department of the University of Melbourne has enjoyed a unique and profitable history of collaboration with the CMRC/ANMRC. Historically numerical meteorology at the University started in the late 1950's when U. Radok and D. Jenssen adapted the equivalent barotropic model of Charney *et al.* (1950) to the Australian region using the University's first electronic digital computer CSIRAC (Radok and Jenssen, 1961). The barotropic model was also extended to include heat exchange processes (Jenssen and Radok, 1964) but the application of the models was limited by the computers available at that time. Nevertheless over this period numerical modelling became a standard part of both the undergraduate and graduate teaching program.

Close collaboration between the Meteorology Department and the Bureau of Meteorology, and subsequently with CMRC/ANMRC personnel has occurred over the years. The numerical analysis scheme used for daily operations by the Bureau for many years had its origin in R. Maine's MSc thesis "Automatic numerical weather analysis for the Australian region" in 1966. M. Voice completed an MSc in 1971 on "A barotropic numerical weather prediction experiment for the Australian region". Later the application of primitive equation prediction models in both CMRC research and Bureau operations was the subject of D. Gauntlett's PhD thesis "The application of numerical models to problems of meteorological analysis and prognosis over the southern hemisphere" in 1974.

With the successful development of numerical modelling in the CMRC and the Bureau, the Meteorology Department tended to concentrate more on other topics of research including Antarctic meteorology, the modelling of ice sheets, sea-ice and climate.

In the mid seventies U. Radok of the Meteorology Department and W. Budd (then with the Antarctic Division, Glaciology Section) approached the ANMRC

(R. Clarke, Officer-in-Charge, B. Hunt, D. Gauntlett and W. Bourke) regarding proposals for cooperative work on climate studies using general circulation models (GCMs). The ANMRC provided considerable assistance to the Department of Meteorology in setting up a version of the ANMRC spectral model for climate studies on the University computers. The preliminary aim was to study the model's ability to simulate the observed climate and study the role of a wide range of features in the climate system such as Antarctic sea-ice, topography, extra tropical cyclones, sea surface temperature and cloud cover.

A start was made to the formulation of an interactive sea-ice component for the model by a visiting Research Fellow, T. Keliher. With the appointment of I. Simmonds, already well experienced with GCMs, and spectral models in particular, the Meteorology Department's activities in general circulation modelling became fully established. I. Simmonds carried out studies of the effect of the Antarctic sea-ice on the southern hemisphere climate using the ANMRC spectral model; he also studied the effects of a range of factors on the model climatology with Y.-B. Lin, a visiting meteorologist from Nanking University. These included both topographic and thermal forcing and the role of the Antarctic continent. Since then further studies have been carried out on the effects of cloud, a different boundary layer formulation, and more recently sea surface temperature, the latter in relation to rainfall (Simmonds and Lin, 1981; 1983; Simmonds and Smith, 1984).

To include an adequate treatment of the oceans in the global atmosphere-ocean climate system N. Smith worked as a Research Fellow at the Meteorology Department for three years and successfully developed a deep sea global dynamic ocean model. During this time, frequent interaction occurred with the ANMRC's oceanography group including C. Fandry and R. Hughes.

In the field of southern hemisphere climatology N. Streten and N. Nicholls have interacted with the Meteorology Department and the Antarctic Glaciology Section in studies of the effects of sea-ice, extra tropical cyclone tracks, persistent pressure anomalies, sea surface temperatures and rainfall. N. Nicholls completed his MSc in 1980 on "The nature and possible cause of some aspects of the interannual fluctuations in the Australian monsoon", showing statistical links between ocean and atmosphere behaviour, followed by his PhD in 1982 indicating promising prospects for long range seasonal forecasting in Australia. N. Streten obtained his DSc in 1982 through the Meteorology Department based on his extensive publication record particularly on southern hemisphere and polar synoptic climatology.

With the establishment of the Chair in Meteorology at Melbourne University in 1979 and the increase in the staff of the Meteorology Department to six academic positions the Department has been able to maintain its activities in numerical modelling. The continued work of T. Gibson, W. Wright, S. Kep, P. Whetton and I. Simmonds on climate and general circulation using both observational and modelling techniques still provides an avenue of long term cooperation even with the organizational changes now overtaking the ANMRC.

After retiring as Officer-in-Charge, ANMRC, R. Clarke continued research as a Senior Associate of the Meteorology Department. During this time he obtained a DSc degree through the Department based on his extensive publication record encompassing boundary layer measurements and numerical modelling, particularly with regard to the mesoscale phenomena; he also continued both field work and numerical modelling to study very successfully the northern Australian Morning Glory phenomenon.

In addition to the many research interactions the Department of Meteorology has had the benefit of a number of ANMRC research staff presenting lecture courses at the University. The regular seminar series run by ANMRC in conjunction with the other research institutes additionally has provided a very valuable forum for presenting highlights of recent research results to the local meteorology community.

The high international reputation which the ANMRC has established has been influential in attracting a continual stream of eminent meteorologists from around the world to visit Melbourne. The Meteorology Department has benefitted from these visits and the colloquia sponsored by ANMRC.

The success, productivity and accomplishments of the ANMRC stand as a landmark to a fruitful collaboration between the CSIRO and the Bureau of Meteorology with the whole meteorology community benefitting as a consequence.

The achievements of the individuals and the group as a whole present a challenge to the new organizational research structures of the Bureau of Meteorology and the CSIRO Division of Atmospheric Research to emulate and excel.

The Meteorology Department of the University of Melbourne recognises the considerable achievements of the ANMRC with the hope of being able to continue and to expand the cooperation in the future through the new organizations.

References

CHARNEY, J., R. FJORTOFT and J. VON NEUMANN (1950). Numerical integration of the barotropic vorticity equation. **Tellus**, 2: 237–254.

JENSSEN, D. (1966). Theoretical outline of a family of one level models for numerical forecasting in the southern hemisphere. **Aust. Met. Mag.,** 14: 1–21.

JENSSEN, D. and U. RADOK (1964). Diabatic heating and cooling in the equivalent-barotropic atmostphere. **Nature**, 202: 1104–1105.

RADOK, U. and D. JENSSEN (1961). Numerical tracing of atmospheric events. **Nature**, 190: 247-248.

SIMMONDS, I. (1980). The effect of sea ice on a general circulation model of the southern hemisphere. IAHS Pub. No. 131: 193–206.

SIMMONDS, I. and Y.-B. LIN (1981). The effect of Antarctica on the high latitude pressure distribution. In **Antarctica: Weather and Climate**, Roy. Meteor. Soc. Aust. Branch, Melbourne, 167–175.

SIMMONDS, I. and Y.-B. Lin (1983). Topographic and thermal forcing in a general circulation model of the southern hemisphere — January case. Meteorology Department, University of Melbourne, Pub. No. 24, 88 pp.

SIMMONDS, I. and I.N. SMITH (1984). A general circulation model study of the effect of global sea surface temperature anomalies on rainfall in the Australian region. Conference on Australian Rainfall Variability, 6–8 August 1984, Arkaroola, South Australia.

IMPACT OF THE CENTRE'S RESEARCH

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In the last 18 years, it was a remarkable and enjoyable experience for me to have opportunities to be associated with a number of long term visitors from CMRC/ANMRC to the GFDL, such as R.H. Clarke, B.G. Hunt, D.J. Gauntlett, W. Bourke and K. Puri, although the first two visitors came to GFDL prior to the establishment of the Centre. Probably because of this acquaintance, I am now requested to write my view on the titled subject. However, among the whole activities of the Centre, i.e., numerical weather prediction, climate research, diagnostic studies, and tropical research, I know only the area of numerical weather prediction. Accordingly, this article would be biased to a certain direction.

First of all, the Centre has been a unique and important establishment in the Australian community of meteorology, and it has satisfactorily accomplished the original objective. Although the Centre is a joint institution of CSIRO and the Department of Science and Technology, it has been independent from both, and thus has been able to concentrate on accomplishing the mission, i.e., implementation of the numerical weather forecasts. The full achievement of the task is prerequisite for pursuing the research. From the standpoint of the research, the Centre has also been successful and has afforded an immeasurable degree of stimulation, and perhaps, guidance to the research community of Australia as well as of the world.

In the following, I will describe my perception of the Centre's impact, selecting only few items. They are: A. — the spectral model; B. — the southern hemisphere weather maps; C. — the climate research; D. — the limited domain modelling; and E. — El Nino and Southern Oscillation.

A. Spectral model

The impact of this model is indeed fantastic. At present it is widely in use at a number of operational weather centres, meteorological research institutions and universities. Bourke is literally a father of the era of spectral model, proliferating a model in the barotropic version around the world.

In 1969, when Bourke changed his professional career from nuclear physicist to meteorologist, he was assigned in CMRC (Tucker was Officer-in-Charge) to visit the Dynamic Prediction Research Unit, Montreal, Canada. This decision was crucial and excellent for the subsequent development of the spectral model, because this travel was extremely timely; the place was most appropriate; and the host institution has competent scientists. At that time (1970), the 'transform' spectral model had just been devised by Orszag (1970) and Eliasen *et al.* (1970). Different from the conventional 'interaction' spectral model, the transform model was very efficient in calculation and was flexible for incorporation of radiation, condensation and other physics. In Montreal, there was Robert, who was an expert on the conventional spectral modelling and who was enthusiastic and charismatic. In this situation and environment, Bourke completed building a barotropic model (Bourke, 1972) utilizing the efficient calculation algorithm and the semi-implicit scheme (Robert, 1969).

This pioneering work is the base of today's success of the spectral prediction model and the spectral general circulation model (GCM). There are now many descendants of this model. For example, the second generations are found in Melbourne, Australia (Bourke, 1974; Puri and Bourke, 1974; Bourke *et al.*, 1977; McAvaney *et al.*, 1978); Montreal, Canada (Daley *et al.*, 1976); Reading, UK (Hoskins and Simmons, 1975), GFDL, USA (Gordon and Stern, 1974; 1982); and NMC, USA (Sela, 1980). The third generations include ECMWF, UK (Baede and Hansen, 1977; Jarraud *et al.*, 1981); and GFDL, USA (Manabe and Hahn, 1981). NCAR, USA (so-called Community Climate Models of version OA and OB) uses the spectral model.

The first operational forecast with the spectral model was in January 1976 at the Bureau of Meteorology, Melbourne, Australia, and three or four weeks later, Montreal, Canada, also started the operational model for short range forecasts. Three major operational centres have recently switched operational models from finite difference to spectral models: NMC, USA (R40-Rhomboidal 40); ECMWF, UK (T63-Triangular 63); and JMA Electronic Computation Centre, Japan (T42).

B. The southern hemisphere weather maps

In general, observational findings give a great deal of stimulus to researchers, particularly in the cases where intriguing processes or phenomena are involved. Weather maps may not be exactly in this category, but in the case of southern hemisphere, the daily weather maps offer immense challenge and excitement, simply because the nature of atmospheric circulations are yet to be unravelled.

There are two aspects in this connection. One is the diagnostic analysis of 15 year series of weather maps, and the other is the consideration of observation system and data assembling.

It should be made clear here that the weather maps have been produced by the Bureau of Meteorology at Melbourne (the World Meteorological Centre), and not by the ANMRC. However, I presume that the computer process of southern hemisphere weather maps has been advanced by the demand of daily numerical weather forecasts. The current analysis system which is over 12 years old was developed by R.S. Seaman and D.J. Gauntlett of the ANMRC, in collaboration with the Bureau of Meteorology (Gauntlett *et al.,* 1972).

This wealth of meteorological treasure has been gradually exploited. Hartman (1976) utilized the tropospheric analysis of Melbourne for his stratospheric studies. Trenberth (1980, 1981a, 1981b, 1982) and Swanson and Trenberth (1981) used the May 1972 — November 1980 series of the WMC maps for diagnostic studies of the southern hemisphere circulation. They found that the Melbourne maps are successful in delineating the characteristic patterns associated with storm tracks, blockings and other transient eddies. There is a number of more recent works, such as Le Marshall and Kelly (1981).

In order to construct a unified picture of our global atmospheric circulation, or to advance our understanding of the northern hemisphere circulation, it is absolutely necessary to explore the process and mechanism of the southern hemisphere circulation as well. There is another point. For the extended range forecast in the northern hemisphere, the global data rather than only the northern hemisphere data have been used conventionally. Although the compelling reason for this treatment has not been known, there is a feeling that the hemispheric interaction may play a crucial role in the evolution of atmosphere beyond the time scale of 10 days in connection with the so-called critical latitude (Webster and Holton, 1982).

The second aspect is the observational system and the data assimilation process. There is no doubt that the satellite observation is vital for the southern hemisphere analysis. It is also important to use an appropriate assimilation technique for dynamical consistency. This is the so-called four dimensional data assimilation. In this respect, there is a number of important contributions from the Centre (for example, Daley and Puri, 1980; Puri, 1981 and Bourke, 1982; Bourke *et al.,* 1982; Puri *et al.,* 1982). GFDL, for example, has benefited from these works for the improvement of the four dimensional data assimilation system.

C. The climate research

In the Centre's activity of the climate research, there was a number of people involved, and the research area ranges from the effect of sea surface temperature on the atmosphere to the air-sea coupled model. Among them, Hunt is a central figure. He was originally a photochemist and was one of the first who incorporated the photochemical process into an atmospheric dynamical model (Hunt, 1966; 1972). His work on the development of the 18-level GCM (Manabe and Hunt, 1968) at GFDL is now a classic in stratospheric studies. After joining CMRC, he continued to carry out this pioneering study, developing the 54-level semi-spectral GCM, which extends up to 100 km (Hunt, 1974; Voice and Hunt, 1975; Hunt 1981a). A corresponding GCM in the northern hemisphere is the 40-level model of Mahlman in GFDL, which extends up to 80 km (Manabe and Mahlman, 1976), although Hunt's model does not include the orography.

Hunt wrote a number of papers successively on a great variety of issues from pollution to the paleoclimate, using the numerical simulation approach, (the N_2 transport, inertial instability in the equatorial upper stratosphere, solar-weather relationship, effect of earth's rotation and obliquity change, effect of volcanoes, impact of cloud albedo changes induced by atmospheric pollution, the 2-day wave in the summer upper atmosphere, and death of the atmosphere) (Hunt, 1973; 1974; 1976; 1977; 1979a; 1979b; 1981a; 1981b; 1981c; 1982). All issues are extremely attractive and provocative. Hunt claims to have opened up many new problems and to have the most comprehensive simulation studies. However, some of his conclusions remain controversial.

Anyway, all these activities are an important part of the Centre's research as I perceived from the standpoint of my limited expertise.

D. The limited domain modelling

The limited domain modelling is one of the important research activities in the Centre, which has a large local impact.

A limited area, six-level primitive equation model has been developed to provide improved 36 hour forecasts for the Australian region. The model includes semi-implicit time differencing, and a nesting procedure which enables boundary values to be updated from the hemispheric spectral model (Gauntlett, 1975; Gauntlett *et al.*, 1976; 1978). The fine quality of the model has been proved based on a number of test cases (McGregor *et al.*, 1978), and this model was implemented for operational use during September 1977, by the Bureau of Meteorology at Melbourne.

A recent review by Anthes (1983) on meso $-\alpha$ scale prediction models (using the horizontal resolution of 20–150 km grid) has quoted the ANMRC as one of the active groups around the world in this research area. Currently, a movable fine mesh model has also been developed. Leslie *et al.* (1981) showed that an improved analysis scheme can make a significant positive impact on the forecast. Enhanced data associated with FGGE improved the S1 skill score for the sea level pressure prognosis.

A novel aspect is the non-linear normal mode type initialization for a limited domain (Bourke and McGregor, 1983). Another point is a study of 'Southerly Buster' (Gauntlett *et al.*, 1984). This is an interesting Kelvin wave phenomenon, which is generated by a combination of orography and a front. Similar phenomena can be found in other parts of the world.

E. El Nino and Southern Oscillation

These phenomena are spectacular and their influence on the world weather is indeed profound.

The research has been conducted on-and-off since the British and Dutch colonial age (for example, Lockyer and Lockyer, 1904; Walker and Bliss, 1930; Berlage, 1957). Australia is located at a strategically most favorable position. The ANMRC has succeeded this tradition with work such as Streten (1975; 1981), Nicholls (1977; 1979a; 1981), Nicholls and Woodcock (1981) and Nicholls *et al.* (1982).

Recently the international focus of attention has been directed to the origin of Southern Oscillation. In this respect, the studies of Streten (1977), Streten and Troup (1973), and Nicholls (1979b) may be quite relevant. Anyway, it looks to me that this area of research in Australia will continue to be most promising.

References

ANTHES, R.A. (1983). Review. Regional models of the atmosphere in middle latitudes. **Mon. Wea. Rev.**, 111: 1306–1335.

BAEDE, A.P.N. and A.W. HANSEN (1977). A ten-day high resolution nonadiabatic spectral integration: A comparative study. European Centre for Medium Range Forecasts. Tech. Rep. No. 7, 82 pp.

BERLAGE, H.P. (1957). Fluctuations of the general atmospheric circulation of more than one year, their nature and prognostic value. **K. Ned. Meteor. Inst., Medel. Verh.**, 69, 152 pp.

BOURKE, W. (1972). An efficient, one-level, primitive equation spectral model. **Mon. Wea. Rev.**, 100: 683–689.

BOURKE, W. (1974). A multi-level spectral model. I. Formulation and hemispheric integrations. **Mon. Wea. Rev.**, 102: 687–701.

BOURKE, W., B. McAVANEY, K. PURI and R. THURLING (1977). Global modelling of atmospheric flow by spectral methods. In: **Methods in Computational Physics**, 17, General Circulation Models of the Atmosphere (J. Chang, ed.), Academic Press, 267–324.

BOURKE, W., K. PURI, R. SEAMAN, B. McAVANEY and J. LE MARSHALL (1982). ANMRC data assimilation for the southern hemisphere. **Mon. Wea. Rev.**, 110: 1749–1771.

BOURKE, W. and J.L. McGREGOR (1983). A non-linear vertical mode initialization scheme for a limited area prediction model. **Mon. Wea. Rev.**, 111: 2285–2297.

DALEY, R., C. GIRARD, J. HENDERSON and I. SIMMONDS (1976). Short-term forecasting with a multi-level spectral model. **Atmosphere**, 14: 98–134.

DALEY, R. and K. PURI (1980). Four-dimensional data assimilation and the slow manifold. **Mon. Wea. Rev.**, 108: 85–99.

ELIASEN, E., B. MACHENHAUER and E. RASMUSSEN (1970). On a numerical method for integration of the hydrodynamical equations with a spectral representation of the horizontal fields. Rep. No. 2, Institute for Theoretical Meteorology, Copenhagen University, Haraldsgade 6, DK 2200, Copenhagen N. Denmark, 37 pp.

GAUNTLETT, D.J. (1975). The application of numerical models to the problems of meteorological analysis and prognosis over the southern hemisphere. Australian Bureau of Met. Study, No. 28.

GAUNTLETT, D.J., L.M. LESLIE and D.R. HINCKSMAN (1976). A semi-implicit forecast model using the flux form of the primitive equations. **Quart. J. Roy. Meteor. Soc.**, 102: 203–217.

GAUNTLETT, D.J., L.M. LESLIE and L.W. LOGAN (1984). Numerical experiments in meso-scale prediction over south east Australia. **Mon. Wea. Rev.**, 112: 1170–1182.

GAUNTLETT, D.J., L.M. LESLIE, J.L. McGREGOR and D.R. HINCKSMAN (1978). A limited area nested numerical weather prediction model: Formulation and preliminary results. **Quart. J. Roy. Meteor. Soc.**, 104: 103–117.

GAUNTLETT, D.J., R.S. SEAMAN, W.R. KININMONTH and J.C. LANGFORD (1972). An operational evaluation of a numerical analysis-prognosis system for the southern hemisphere. **Aust. Met. Mag.**, 20: 61–82.

GORDON, C.T. and W. STERN (1974). Spectral modelling at GFDL. The GARP Programme on Numerical Experimentation. Rep. Int. Symp. on Spectral Methods in Numerical Weather Prediction, Copenhagen, WMO, Rep. No. 7, 46–80.

GORDON, C.T. and W.F. STERN (1982). A description of the GFDL global spectral model. **Mon. Wea. Rev.**, 110: 625–644.

HARTMANN, D.L. (1976). The structure of the stratosphere in the southern hemisphere during late winter 1973 as observed by satellite. **J. Atmos. Sci.**, 33: 1141–1154.

HOSKINS, B.J. and A.J. SIMMONS (1975). A multi-layer spectral model and the semi-implicit method. **Quart. J. Roy. Meteor. Soc.**, 101: 637–655.

HUNT, B.G. (1966). Photochemistry of ozone in a moist atmostphere. **J. Geophys. Res.**, 71: 1388–1398.

HUNT, B.G. (1972). Photochemical heating of the mesosphere and lower thermosphere. **Tellus**, 24: 47–55.

HUNT, B.G. (1973). Zonally symmetric global general circulation models with and without the hydrologic cycle. **Tellus**, 25: 337–354.

HUNT, B.G. (1974). A global general circulation model of the atmosphere based on the semi-spectral model. **Mon. Wea. Rev.**, 102: 3–16.

HUNT, B.G. (1976). On the death of the atmosphere. **J. Geophys. Res.**, 81: 3677–3687.

HUNT, B.G. (1977). A simulation of the possible consequences of a volcanic eruption on the general circulation of the atmosphere. **Mon. Wea. Rev.**, 105: 247–260.

HUNT, B.G. (1979a). The influence of the Earth's rotation rate on the general circulation of the atmosphere. **J. Atmos. Sci.**, 36: 1392–1408.

HUNT, B.G. (1979b). The effects of past variations of the Earth's rotation rate on climate. **Nature**, 281: 188–191.

HUNT, B.G. (1981a). The maintenance of the zonal mean state of the upper atmosphere as represented in a three-dimensional general circulation model extending to 100 km. **J. Atmos. Sci.**, 38: 2172–2186.

HUNT, B.G. (1981b). An evaluation of a sun-weather mechanism using a general circulation model of the atmosphere. **J. Geophys. Res.**, 86: 1233–1245.

HUNT, B.G. (1981c). The 2-day wave in the middle atmosphere as simulated in a general circulation model extending from the surface to 100 km, **J. Atmos. Terr. Phys.**, 43: 1143–1154.

HUNT, B.G. (1982). The impact of large variations of the Earth's obliquity on the climate. **J. Meteor. Soc. Japan,** 60: 309–318.

JARRAUD, M., C. GIRARD and U. CUBASCH (1981). Comparison of medium range forecasts made with models using spectral or finite difference techniques in the horizontal. Tech. Rep. No. 23, European Centre for Medium Range Weather Forecasts, 95 pp.

LE MARSHALL, J.F., and G.A.M. KELLY (1981). A January and July climatology of the southern hemisphere based on daily numerical analyses 1973–1977. **Aust. Met. Mag.**, 29: 115–123.

LESLIE, L.M., G.A. MILLS and D.J. GAUNTLETT (1981). The impact of FGGE data coverage and improved numerical techniques in numerical weather prediction in the Australian region. **Quart. J. Roy. Meteor. Soc.**, 107: 629–642.

LOCKYER, N. and W.J.S. LOCKYER (1904). The behaviour of the short-period atmospheric pressure variation over the earth's surface. **Proc. Roy. Soc. London**, 73: 457–470.

MANABE, S. and B.G. HUNT (1968). Experiments with a stratosphere general circulation model. Part I. Radiative and dynamic aspects. **Mon. Wea. Rev.**, 96: 477–502.

MANABE, S. and J.D. MAHLMAN (1976). Simulation of seasonal and interhemispheric variations in the stratospheric circulation. **J. Atmos. Sci.**, 33: 2185–2217.

MANABE, S. and D.G. HAHN (1981). Simulation of atmospheric variability. **Mon. Wea. Rev.**, 109:2260–2286.

McAVANEY, B.J., W. BOURKE and K. PURI (1978). A global spectral model for simulation of the general circulation. **J. Atmos. Sci.**, 35: 1557–1583.

McGREGOR, J.L., L.M. LESLIE and D.J. GAUNTLETT (1978). The ANMRC limited-area model: Consolidated formulation and operational results. **Mon. Wea. Rev.**, 106: 427–438.

NICHOLLS, N. (1977). Tropical-extratropical interactions in the Australian region. **Mon Wea. Rev.**, 105: 826–832.

NICHOLLS, N. (1979a). A possible method for predicting seasonal tropical cyclone activity in the Australian region. **Mon Wea. Rev.**, 107: 1221–1224.

NICHOLLS, N. (1979b). A simple air-sea interaction model. **Quart. J. Roy. Meteor. Soc.**, 105: 93–105.

NICHOLLS, N. (1981). Air-sea interaction and the possibility of long-range weather prediction in the Indonesian archipelago. **Mon Wea. Rev.**, 109: 2435–2443.

NICHOLLS, N. and F. WOODCOCK (1981). Verification of an empirical long-range weather forecasting technique. **Quart. J. Roy. Meteor. Soc.**, 107: 973–976.

NICHOLLS, N., J.L. McBRIDE and R.J. ORMEROD (1982). On predicting the onset of the Australian wet season at Darwin. **Mon. Wea. Rev.**, 110: 14–17.

ORSZAG, S.A. (1970). Transform method for calculation of vector-coupled sums: application to the spectral form of the vorticity equation. **J. Atmos. Sci.**, 27: 890–895.

PURI, K. (1981). Local geostrophic wind correction in the assimilation of height data and its relationship to the slow manifold. **Mon Wea. Rev.**, 109: 52–55.

PURI, K. and W. BOURKE (1974). Implications of horizontal resolution in spectral model integrations. **Mon Wea. Rev.**, 102: 333–347.

PURI, K. and W. BOURKE (1982). A scheme to retain the Hadley circulation during non-linear normal mode initialization. **Mon Wea. Rev.**, 110: 327–335.

PURI, K., W. BOURKE and R. SEAMAN (1982). Incremental linear normal mode initialization in four-dimensional assimilation. **Mon Wea. Rev.**, 110: 1773–1785.

ROBERT, A.J. (1969). The integration of a spectral model of the atmosphere by the implicit method. Proceedings of WMO/ICSU Symposium on Numerical Weather Prediction, Tokyo, November, 1968, S-VII, 19–24.

SELA, J.G. (1980). Spectral modelling at the National Meteorological Centre. **Mon Wea. Rev.**, 108:1279–1292.

STRETEN, N.A. (1975). Satellite derived inferences to some characteristics of the South Pacific atmospheric circulation associated with the Nino event of 1972–73. **Mon Wea. Rev.**, 103: 989–995.

STRETEN, N.A. (1977). Seasonal climatic variability over the Southern Ocean. **Arch. Met. Geoph. Biokl.**, Ser. B, 25: 1–19.

STRETEN, N.A. (1981). Southern hemisphere sea surface temperature variability and apparent associations with Australian rainfall. **J. Geophys. Res.**, 86: 485–497.

STRETEN, N.A. and A.J. TROUP (1973). A synoptic climatology of satellite observed cloud vortices over the southern hemisphere. **Quart. J. Roy. Meteor. Soc.**, 99: 56–72.

SWANSON, G.S. and K.E. TRENBERTH (1981). Trends in the southern hemisphere tropospheric circulation. **Mon Wea. Rev.**, 109: 1879–1889.

TRENBERTH, K.E. (1981a). Observed southern hemisphere eddy statistics at 500 mb: frequency and spatial dependence. **J. Atmos. Sci.**, 38: 2585–2605.

TRENBERTH, K.E. (1981b). Seasonal variations in global sea level pressure and the total mass of the atmosphere. **J. Geophys. Res.**, 86: 5238–5246.

TRENBERTH, K.E. (1982). Seasonality in southern hemisphere eddy statistics at 500 mb. **J. Atmos. Sci.**, 39: 2507–2520.

VOICE, M.E. and B.G. HUNT (1975). Southern hemisphere forecasting experiments with a semi-spectral model. **Mon. Wea. Rev.**, 103: 1077–1088.

WALKER, G.T. and E.W. BLISS (1930). World weather IV. **Mem. Roy. Meteor. Soc.**, 3:81–95.

WEBSTER, P.J. and J.R. HOLTON (1982). Cross-equatorial response to middle-latitude forcing in a zonally varying basic state. **J. Atmos. Sci.**, 39: 722–733.

NOAA/NESDIS (NESS) AND ANMRC (CMRC)

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Chief US Department of Commerce (USDC) NOAA NESS Radiation Branch 1966–1977; Chief USDC NOAA NESS Mesoscale Applications Branch 1977–1980, Director USDC NOAA NESDIS Research and Application Development Laboratory, and Associate Director Space Science Engineering Center, University of Wisconsin from 1980.

For more than a decade, United States and Australian scientists, from the National Earth Satellite, Data, and Information Service (NESDIS) and the Australian Numerical Meteorology Research Centre (ANMRC) have worked collaboratively on using satellite sounding observations to improve numerical weather prediction. This collaboration has focused the talent of experts on satellite radiance data interpretation and regional mesoscale numerical weather prediction modelling in order to accelerate the process of greatly improving regional weather forecasts for both countries. Because of the benefits achieved, the collaboration between scientists is to be continued into the future through a cooperative research program to be established between the Australian Bureau of Meteorology Research Centre (BMRC) and NOAA's Cooperative Institute for Meteorological Satellite Studies (CIMSS).

The close collaboration between the CMRC/ANMRC and the NESDIS (formerly the National Environmental Satellite Service (NESS)) of NOAA had its origins at the IAMAP/IAPSO First Special Assemblies held in Melbourne during January 1974. Both W. Smith and D. Wark of NESS were in attendance. During the conference very fruitful discussions were held between G.B. Tucker, Chief CSIRO Division of Atmospheric Physics, D. Gauntlett and G. Kelly of CMRC, and W. Smith and D. Wark of NESS regarding the potential of satellite observations for operational weather forecasting in the southern hemisphere. An invitation was extended to G. Kelly, one of CMRC's experts on satellite meteorology, to visit the NESS in order to see firsthand the developments that were taking place in the United States, especially those developments related to the Satellite Atmospheric Sounding Program. During G. Kelly's visit to NESS in 1975, further cooperative efforts were established between ANMRC and NESS to enhance the science of sounding retrieval from satellite observations of the southern hemisphere.

During 1976, under a cooperative agreement between NOAA, CSIRO and the Australian Bureau of Meteorology, W. Smith (NESDIS) worked for eleven months at CSIRO Division of Atmospheric Physics and the ANMRC with G. Kelly and G. Mills to demonstrate successfully the positive impact of Nimbus-6 sounding data on Australian regional numerical weather forecasts (Kelly *et al.*, 1978). There was close collaboration with J. Le Marshall and P. Powers on the optimization of sounding retrieval methods for the southern hemisphere. The result of the numerical weather prediction (NWP) impact tests and the enhancement of sounding retrieval algorithms was the establishment of a joint Bureau of Meteorology and ANMRC program to implement a direct readout and data handling facility for the TIROS-N/NOAA operational satellite enabling real time processing and operational use of the sounding data in the Bureau's regional forecast model. At the same time, W. Smith recognised the unique attributes of the ANMRC limited area (Australian region primitive equation (ARPE)) model for utilizing satellite sounding data. Since he was to return to Madison, Wisconsin as the Chief of a Mesoscale Applications Branch of NESS, W. Smith requested the ANMRC to modify this model in order to perform mesoscale NWP for the North American region.

Upon W. Smith's return to the United States, a joint NOAA/University of Wisconsin (NOAA/UW) research group was established at the Space Science and Engineering Centre (SSEC) in Madison, Wisconsin. Its charter was to develop methods of using existing polar orbiting and forthcoming geostationary satellite sounding data for mesoscale meteorological studies and weather forecasting. Soon after the launch of the TIROS-N satellite in 1979, G. Kelly, after collaboration with L. Leslie and J. McGregor (ANMRC), worked with W. Smith's group to modify successfully the ANMRC ARPE model to mesoscale resolution for application with high spatial resolution TIROS-N soundings over North America received locally via direct readout at Madison. During the same visit G. Kelly was able to take advantage of NESS/UW software developments for processing direct readout TIROS-N sounding data with high spatial resolution. The NESS/UW software was adopted subsequently for the TIROS-N/NOAA satellite sounding system established by the Bureau of Meteorology in Melbourne.

During G. Kelly's assignment to Wisconsin, a NOAA/UW Cooperative Institute for Meteorological Satellite Studies (CIMSS) was formed and a formal cooperative program between CIMSS and the ANMRC was established. The CIMSS/ANMRC cooperative program provided for: the exchange of satellite sounding and NWP model software; the exchange of scientists; and, cooperative research on satellite data processing technology and numerical forecasting techniques. In 1982, G. Mills (ANMRC) worked at CIMSS on the application of high resolution NOAA satellite soundings in the mesoscale numerical forecast model to the prediction of severe convective weather events (Mills and Hayden, 1983). As a result of the Kelly and Mills efforts, a mesoscale numerical forecast capability was established at CIMSS for numerical weather prediction studies with satellite data.

After several short term visits of W. Smith (NESS) to ANMRC during 1982 and 1983, J. Le Marshall, formally of ANMRC and currently with the Bureau of Meteorology, worked at the CIMSS on the application of the mesoscale NWP model to the geostationary VAS satellite sounding data for forecasting severe convective weather and tropical storm motions. J. Le Marshall also conducted studies with a newly developed ‘physical’ method of retrieving soundings from TIROS-N/NOAA direct readout data in preparation for its eventual implementation at the Bureau of Meteorology, Melbourne.

Thus the NESDIS (NESS)/ANMRC (CMRC) collaboration has existed over one decade. The association has been extremely fruitful: software was developed and implemented at the Bureau of Meteorology for the real time processing and operational use of TIROS-N/NOAA polar orbiting satellite sounding data; and a mesoscale numerical weather prediction model was established at the NOAA/UW facility for conducting studies to demonstrate the impact of new satellite sounding systems (e.g., VAS) on regional weather analysis and forecasting. As a result of the cooperative research between NESDIS and ANMRC a further program is being established between CIMSS and the BMRC to continue reaping the benefits clearly available to both the United States and Australia.

References

KELLY, G.A.M., G.A. MILLS and W.L. SMITH (1978). Impact of Nimbus-6 temperature soundings on Australian region forecasts. **Bull. Amer. Meteor. Soc.**, 59: 393–405.

MILLS, G.A. and C.M. HAYDEN (1983). The use of high horizontal resolution satellite temperature and moisture profiles to initialize a mesoscale numerical weather prediction model — a severe weather event case study. **J. Clim. Appl. Meteor.**, 22: 649–663.

V. BEYOND ANMRC

J.W. ZILLMAN, BA MSc PhD FTS

Joined the Bureau of Meteorology 1957; Assistant Director (Research) 1974–1978; Director of Meteorology since 1978. Member ANMRC Advisory Committee 1978–1979.

N.H. FLETCHER, MA PhD DSc (Sydney) FAA

CSIRO Division of Radiophysics 1956–1960; Professor of Physics UNE 1963–1983; Director CSIRO Institute of Physical Sciences since 1983.

D.J. GAUNTLETT, BSc PhD

Joined the Bureau of Meteorology 1959; Bureau Officer in CMRC/ANMRC 1969–1975; CSIRO Principal Research Scientist with ANMRC 1975–1978; Officer-in-Charge ANMRC 1978–1983; Deputy Director (Research and Systems) Bureau of Meteorology since 1983.

G.B. TUCKER, BSc DIC PhD

Assistant Director Research and Development, Bureau of Meteorology 1965–1969; Officer-in-Charge CMRC 1969–1973; Chief CSIRO Division Atmospheric Physics 1973–1983; Chief CSIRO Division of Atmospheric Research since 1983. CMRC Committee 1969–1973; ANMRC Advisory Committee 1974–1979.

In view of the scientific achievements of the ANMRC as described in the preceding summary profiles, the reasons for closing ANMRC and the adoption of new administrative arrangements and scientific directions are important considerations which deserve comment. From the Bureau point of view the Centre has always represented an unsatisfactory compromise between what the Bureau aspired to achieve in its statutory role as a national meteorological agency and what it could actually achieve given the administrative constraints operating within the Australian Public Service. This view was expressed in a number of relevant scientific reviews and was specifically addressed by the 1976 Committee of Inquiry into the Bureau of Meteorology (CIBM). In particular, CIBM called for a strengthening of the Bureau's in-house research capacity to meet its statutory responsibilities. At about the same time an independent Inquiry into CSIRO, while recognising that CSIRO currently undertakes the bulk of Australian basic research in meteorology, called for this research to be rationalized with the research programs of the Bureau.

In an integrated sense the relevant findings of these Inquiries reflected a general uneasiness concerning the organization and effectiveness of the **total** Australian Government funded meteorological research effort and its capacity to respond to the new directions which were emerging within the science of meteorology. Within CSIRO major scientific adjustments were also about to take place with decisions to phase out weather modification (cloud seeding) research and programs involving aspects of routine monitoring (ozone networks). There was also a strong perception that local research into numerical meteorology had developed to the point where a specific institutional emphasis in the field was becoming less necessary. In short, while scientific problems transcend institutional divisions, there was an appropriate scientific climate and strong administrative and budgetary pressure to rationalize the conduct of Australian research in the atmospheric sciences.

The formal instrument of rationalization was the 1981 Review of Commonwealth Functions (RCF). Specifically, as a result of the RCF it was decided that the ANMRC should be closed and CSIRO's responsibilities for ozone monitoring should be transferred to the Bureau. As part of the rationalization process decisions were also made on the future division of research responsibilities between the Bureau and CSIRO. These responsibilities were outlined as follows:

> "The Bureau of Meteorology, as the national meteorological service for Australia, will have primary responsibility for research in support of its own operations and services, including research directed to the broad delineation of the characteristics of Australian weather and climate and for liaison with the World Meteorological Organization in relation to relevant research in Australia.
>
> CSIRO's primary role will be to carry out research into physical and chemical aspects of atmospheric processes and phenomena, especially basic aspects and those related to environmental and industrial problems, and to community needs, bearing in mind the role of the Bureau."

The focus for the Bureau's future research activities will be the new Bureau of Meteorology Research Centre (BMRC) which will function fairly much as a self-contained research institute under broad Bureau auspices. Its role will be to serve as a national meteorological research agency and to conduct research in support of the Bureau's service requirements. Important aspects of the BMRC structure will be the provision of Research Scientist staff classifications and the appointment of high level scientific leadership. CSIRO meanwhile has already consolidated its atmospheric science research into a new Division of Atmospheric Research (DAR).

At this stage it is a little premature to map out in close detail the future research programs of both BMRC and DAR. However some broad comments on new directions for research into weather and climate are possible. To aid in this it is useful to attempt to classify the effort devoted to meteorological research over the past 25 years or so. One useful way to do this is to consider a gross sub-division according to the space-time scales of phenomena involved: small-short, medium, and large-long scales. Medium scales will be regarded as those of the synoptic phenomena that have been the principal concern of national weather services since their inception around the turn of the century, having orders of magnitude of 10^3 km and 1–10 days. Large-long scales involve planetary phenomena, both hemispheric and global, and climatic scale processes, having orders of magnitude of 10^4 km and months and beyond. Small-short scales cover micro-meteorological and meso-meteorological phenomena, having orders of magnitude less than 10^2 km and fractions of a day.

From the 1950's to the beginning of GARP, in the mid 1960's, the focus of attention of meteorological researchers was on the small and medium scales, with perhaps most scientific progress being made in micro-meteorology and the understanding of exchange mechanisms across the earth's surface and through the lowest layers of the atmosphere. Of course many observational discoveries of the atmospheric structure and behaviour on the medium scale had been made and some fundamental theorems usefully applied to describe this behaviour, notably the conservation of vorticity and the applicability of the Navier Stokes equations. But in general, and certainly in Australia, micro-meteorology was the main scene of scientific understanding. There was a smaller interest in climate except to the extent that global budgets of energy, momentum and water had been drawn up.

With the coming of GARP (and CMRC), activities concerned with the medium scale, the first GARP objective* became the major focus of activity. Considerable advances in understanding synoptic processes occurred, principally due to rapid improvement in computer technology, new observing systems (particularly those involving satellites) and a more accurate handling of the numerics associated with solving the equations of motion. However, by the time of the Global Weather

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* "The Global Atmospheric Research Programme (GARP) is a programme for studying those physical processes in the troposphere and stratosphere that are essential for an understanding of:

(a) The transient behaviour of the atmosphere as manifested in the large-scale fluctuations which control changes of the weather; this would lead to increasing the accuracy of forecasting over periods from one day to several weeks;

(b) The factors that determine the statistical properties of the general circulation of the atmosphere which would lead to better understanding of the physical basis of climate."

(WMO/ICSU GARP Publication Series)

Experiment (the First GARP Global Experiment) in 1979, a general tightening of resources was seriously affecting all nations. For these and other more complex reasons, associated with the competition for funds and the psychological attraction of new initiatives, interest in the second GARP objective* blossomed at the expense of the first. Climate became the new focus and this switch was aided by several environmental concerns, some of which had a sound scientific basis. At this time, too, a school of thought had emerged that linear treatments of the relevant dynamical equations could yield some useful understanding of large scale processes and patterns.

Looking into the future, two questions are apposite: What aspects of weather and climate have so far been relatively intractable to scientific study since 1960? What new scientific techniques and concepts are emerging which have the greatest potential to improve understanding of atmospheric behaviour? The first question represents 'services pull' and the second represents 'science push' in the quest for knowledge.

Two areas of intractability are particularly apparent. First, actual surface weather forecasts have not improved commensurately with the demonstrable increase in skill of forecasting the broad scale (synoptic) pattern. Second, long range forecasting, long a catch-cry, is still far from being a reality — whether we refer to monthly, seasonal or interannual time scales.

Fortunately answers to the second question to some extent parallel those to the first. There are signs that the physics associated with the regional modulation of the broad scale pattern is beginning to be represented adequately. Both on the mesoscale (e.g., the mechanism of frontal systems) and on the microscale (e.g., the effect of complex terrain on the boundary layer) there is some prospect of success from a four-fold attack using field observations, laboratory modelling, numerical modelling and theory. It will not be enough, however, to blindly apply finer and finer mesh numerical models; two other classes of problems have to be solved to ensure progress — the incorporation of the appropriate physics, and the observation of the small scale field for parameterization of yet smaller scale processes and for initialization and validation of any quantitative synthesis of behaviour. On the larger scale it remains to be seen whether linear studies will continue to be profitable, but ways of considering the effect of non-linearity look promising; these include a wider application of low-order climate models and also some new application of concepts from statistical physics to the behaviour of the general circulation. In addition to this, global studies of trace gas distribution, originally primarily of environmental concern, are yielding insight into both inter-hemispheric transport and exchange between the atmosphere and the ocean. Finally, while air-sea interaction and joint atmosphere-ocean modelling are topics of some appeal, the first could involve expensive ship-based observations and the second expensive computer-based studies so that a clear designation not only of scientific objectives but also of new ideas and realistic targets will be a necessary pre-requisite for the mounting of any major attack on these problems.

It is precisely because these problems have remained intractable that they will require both new ideas and the highest quality of scientific attack for solution. Of course, there are still many residual problems associated with the medium scale, notably those concerning the most effective assimilation of observations, particularly satellite observations, and the way in which the atmosphere moves towards recognisable modes of behaviour, such as blocking patterns and index cycles. Nevertheless it is our opinion that over the next decade while research into the larger scale will certainly continue, a deterministic approach to microscale and mesoscale phenomena will receive increased attention. It is likely too, that now that many of the initial technical difficulties associated with numerical modelling have been solved, this approach will take its place in the wider armoury of methods used to study the atmosphere. We can perhaps look forward to a more interactive involvement of different methods than has occurred in the past.

VI. RESEARCH PROGRAM

This chapter highlights the principal achievements of the Centre's research program from 1969 to 1984 in terms of the three subject areas: weather research, observational and diagnostic studies, and climate research. In describing this research below, explicit reference to particular CMRC/ANMRC papers has been omitted. References to external publications however, are included. A full bibliography of CMRC/ANMRC publications is given in Appendix I.

1. WEATHER RESEARCH

W1 ANALYSIS

Overview

Meteorological analysis may be defined as the problem of defining the state of the atmosphere as comprehensively as possible given an irregular distribution in space and time of observations of pressure, temperature and wind. This task of interpolating discrete data to provide a more or less continuous representation in space and time includes a range of procedures spanning manual analysis through to comprehensive four dimensional numerical objective analysis by computational methods. Numerical weather prediction depends vitally on the quality of such objective numerical analysis, and the Centre's goal of improved prediction demanded substantial research into these methods.

Observations are the raw material for analysis. The challenge of using the largely satellite-based data of the southern hemisphere, in the best possible way, has been a continuing theme of the Centre's research program. In the earlier years, there was great reliance upon satellite data in image (pictorial) form rather than in quantitative form. During this period, the Centre had an active research program both in image interpretation, and in the development of numerical analysis methods designed to make best use of interpretive data. More recently, as much more quantitative data became available from satellites, the research emphasis shifted to focus upon retrieval methods, and the so-called 'four dimensional assimilation' approach to analysis.

A useful spin-off from analysis research has been the development of objective methods to assess quantitatively the impact upon analysis accuracy of changes to the observing network. These methods have found application in a variety of specific problems for network design.

W1.1 Australian Region Objective Analysis

The pioneering work on numerical analysis for the Australian region was commenced in the Bureau of Meteorology prior to the formation of the CMRC (Maine, 1967; Maine and Seaman, 1967). These early efforts were largely responsible for the analysis system implemented by the Bureau in 1970. This system was based upon that which had operated successfully for the northern hemisphere at the US National Meteorological Centre.

It soon became clear that essential differences between the data bases of the southern and northern hemispheres would necessitate the development of new techniques for numerical analysis. The crucial difference at that time was the much greater dependence in the Australian area upon interpretive data derived from satellite imagery. Basically, the problem was to combine interpretive and conventional data in the most appropriate way.

Much of the Centre's research in numerical analysis, in the early years, was directed towards this problem. One approach, which led to some improvement in the quality of analyses above 500 mb, made use of the systematic dependence of the vertical stability structure above 500 mb on low and mid-tropospheric temperatures. Since the 1000 to 500 mb thickness was a quantity which could be interpreted with some skill from satellite imagery, such temperature-stability relationships enabled vertical extrapolations to be made in a more meaningful way. In particular, the tropopause was able to be delineated in a synoptically reasonable manner.

A more substantial impact upon analyses followed from the recognition that it was pattern, or differential geometry, which was best interpreted from satellite imagery. This led to the development of the variational blending technique, a mathematical method based upon the calculus of variations, to combine quantitative observations of geopotential height and wind data with interpreted cloud patterns. Variational blending in two dimensions was incorporated into the Bureau's operational analyses in 1976. A diagram elsewhere in this report (Section W2.2) indicates an improvement in forecast accuracy commencing at about this time. By January 1977 this approach had been extended to allow three dimensional blending of conventional geopotential and wind data at all levels with cloud patterns, and subsequently with the newer form of observational data, such as satellite derived temperature soundings and winds, and ocean buoy data. It was implemented initially for the Australian region and later extended to the hemisphere in anticipation of the increased data analysis requirement during FGGE. The numerical analysis component of regional data impact experiments (see Section W2.2) was based upon variational blending principles.

W1.2 Southern Hemisphere Objective Analysis

For the first half of the lifetime of the Centre less resources were devoted to numerical analysis on a hemispheric scale, than to analysis in the Australian region. This reflected both the relative priorities of the Bureau of Meteorology operations, and the problems of sparse data, which were even more accentuated for the hemisphere than for the region. Developments for the hemisphere largely paralleled those for the region, but were implemented later. From the outset, the hemispheric analysis system was designed for use in an analysis-forecast cycle, with the background field for an analysis being provided by a 12 hour forecast from the previous analysis time. In this respect, its design was a precursor to the strategy developed to greater extent in later work on four dimensional assimilation. Some of the hemispheric analysis-forecast cycling experiments made in the Centre include the real and non-real time evaluations of the baroclinic and primitive equation models in the early 1970's (see Fig. 1); the establishment in 1973 of the requirement to specify a pressure reference level, the temperature field alone being

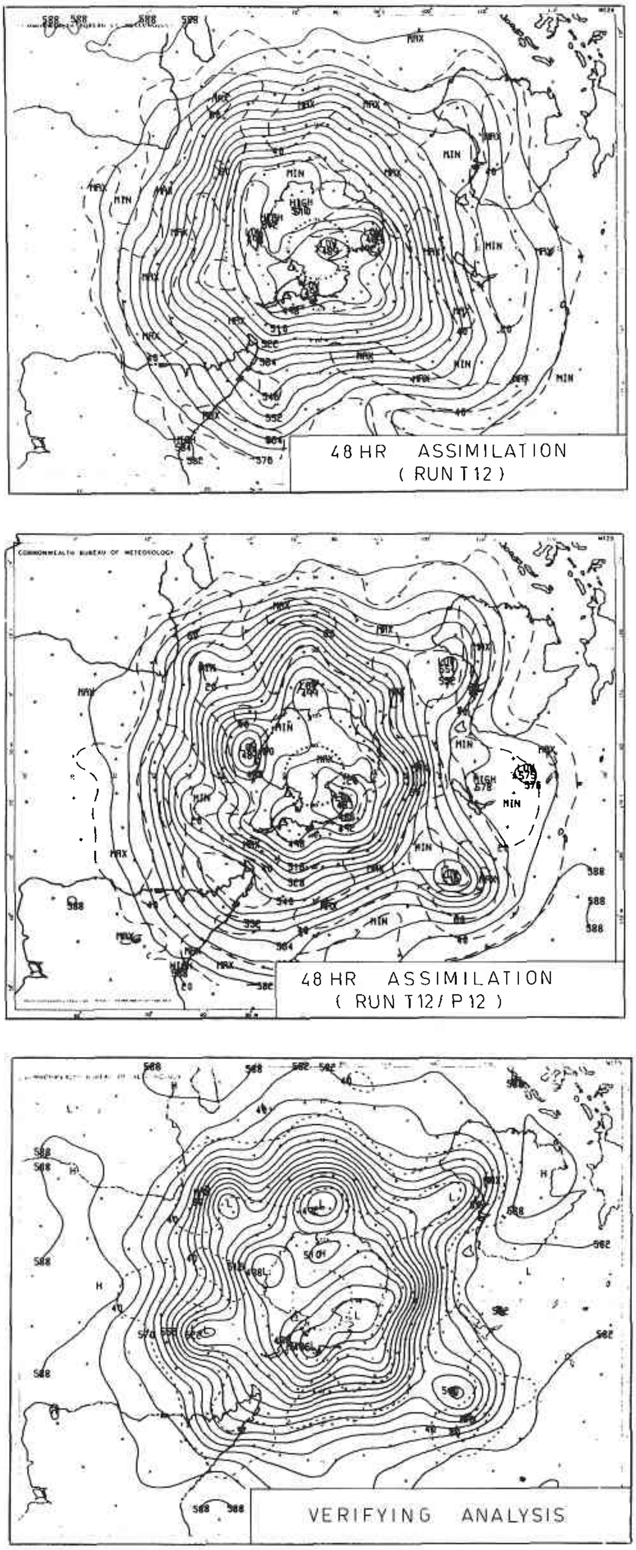


Fig. 1. *A comparison of 48 h assimilation results at 500 mb obtained from the six-level PE model in the early 1970's. The initial analysis was for 1200 GMT 1 November 1969, and data insertion commences at 0000 GMT 2 November 1969. Run T12 is for the exclusive assimilation of temperature, and Run T12/P12 for the assimilation of temperature and mean sea level pressure. An independent verifying analysis is also shown.*

insufficient to maintain a realistic objective analysis system; assessment of the impact of VTPR satellite data on southern hemisphere analyses and forecasts, during 1976; and, as implied above, four dimensional assimilation tests.

W1.3 Tropical Objective Analysis

Much of Australia lies in tropical latitudes, and it has long been recognised that the performance of (traditional) numerical weather prediction models has been rather poor in these areas. To address this problem, the Centre established a Tropical Research Group in 1979. Concurrent with the development of a numerical system, it has been necessary to gain further insight into the space and time scales, as well as the underlying physical processes, characteristic of tropical phenomena. To this end a number of diagnostic studies has been conducted and these are mentioned in Section D2.1.

One of the main problems in studying the weather systems of the Australian tropics has been insufficient observational data arising from the lack of (and expense to establish) a regularly reporting network of stations, together with the vast expanses of surrounding oceans. The special experiments such as FGGE and MONEX of the mid and late seventies therefore have provided extremely valuable data sets on which to base much of the Group's research.

The first major task in developing a numerical weather prediction system for the Australian tropics was the construction of a suitable analysis scheme. It was decided to analyse wind, temperature and humidity on a regular grid on sigma surfaces using three dimensional univariate optimum interpolation. The scheme developed also allows variable resolution and grid location, and has flexibility with respect both to the data bases for observation input, and the output of analysed fields.

Data from the FGGE year for December 1978 were used to produce the first analyses from this system (see Fig. 2), and these compared favourably with those prepared manually by the Darwin Regional Meteorological Centre (RMC). A real time trial of the system which was conducted in April 1983 with the cooperation of the Darwin RMC, demonstrated its viability. It was modified further, particularly to facilitate ease of use by the operator, and a second trial was conducted in November 1983. This proved to be extremely successful, giving rise to plans for upgrading equipment in the near future, and the continued use of the scheme by Darwin for production of their Tropical Diagnostic Statement.

W1.4 Satellite Data

With its vast ocean expanses and relatively little land, the analysis of southern hemisphere weather patterns has always been at a disadvantage compared to its northern counterpart in its lack of conventional meteorological observations. The advent of the weather satellites in the mid sixties afforded the potential for alleviating this problem. The CMRC/ANMRC therefore has directed considerable effort over the past 15 years to obtain maximum benefit from this resource.

W1.4.1 Pattern Interpretation

In the early seventies satellite observations were principally in the form of cloud pictures which it was found could be interpreted to yield values of the 1000 —

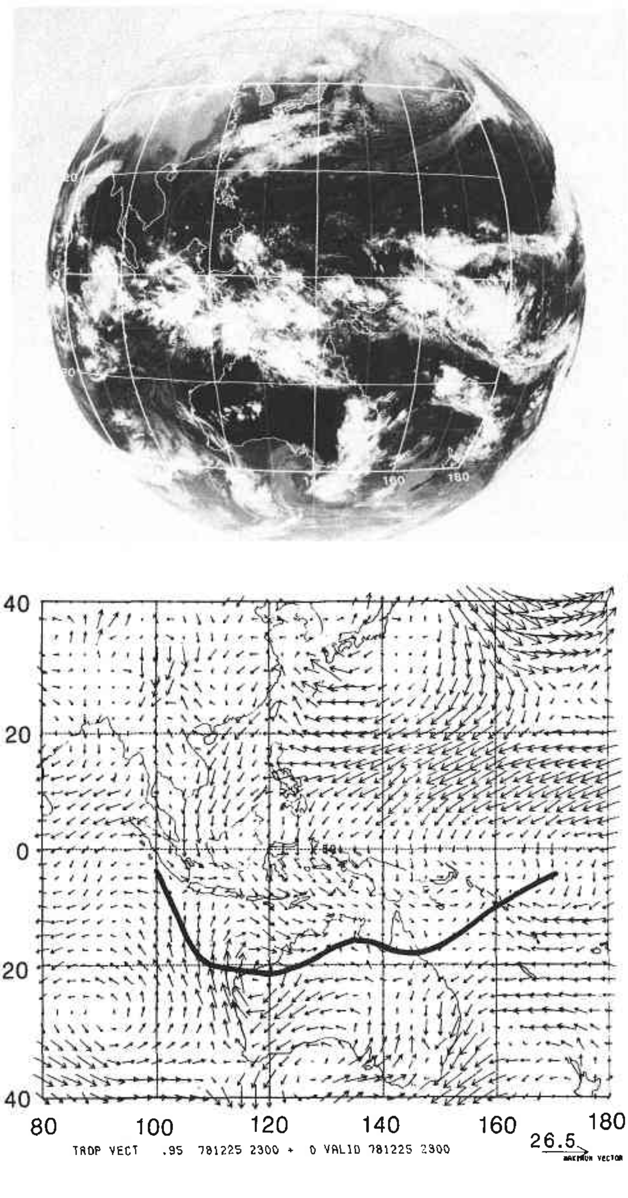


Fig. 2. *The 0000 GMT 26 December 1978 infrared satellite image (upper) and analysed wind field (ms⁻¹) at the model level closest to the surface. The full line denotes the monsoon shear line.*

500 mb geopotential thickness. Diagnostic studies within CMRC developed a vortex classification scheme from which surface pressure, and 500 mb and 300 mb geopotential heights were estimated in terms of anomaly patterns. These were used as a guide for both manual and numerical synoptic analyses over sparse data areas.

Cloud vortex patterns were also used in a method for determining a reference level in data sparse areas. This was required for calculating geopotential height from satellite temperature profiles which first became available in 1973. This scheme was based on the SINAP method developed in the USA (Nagle and Hayden, 1971), and used the statistical patterns of short wave 500 mb height for each stage of

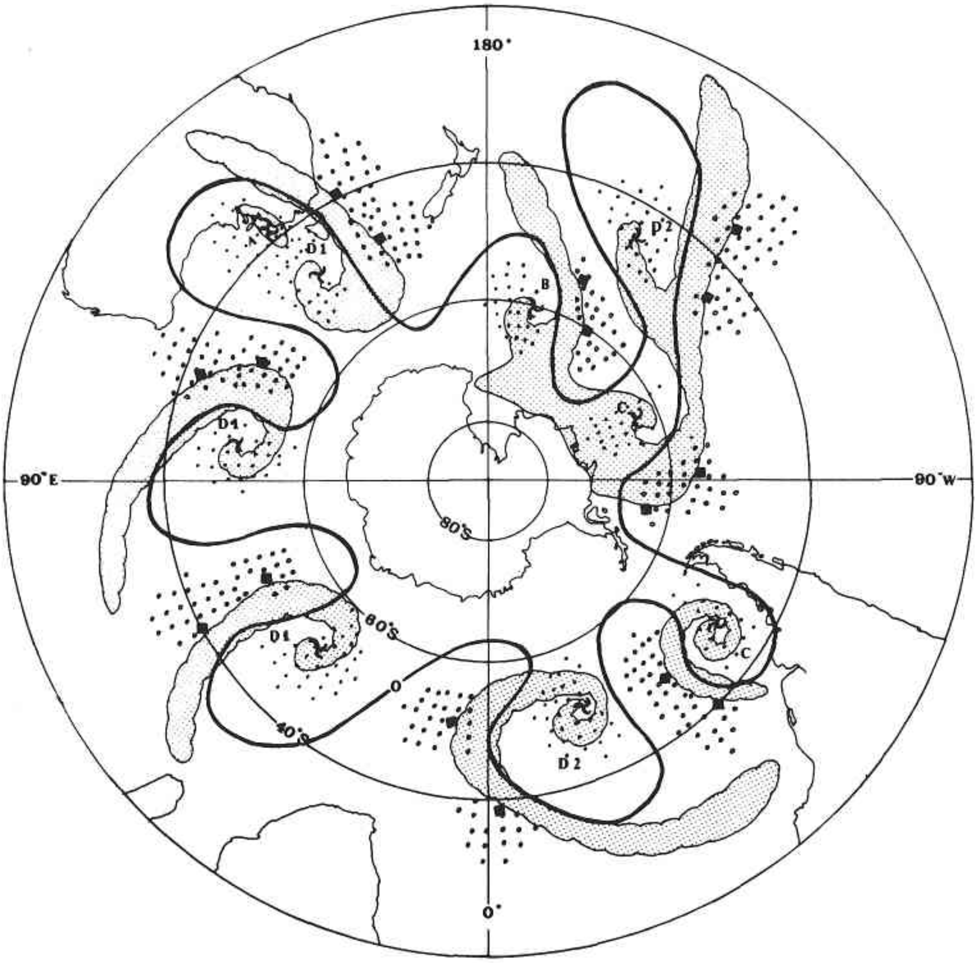


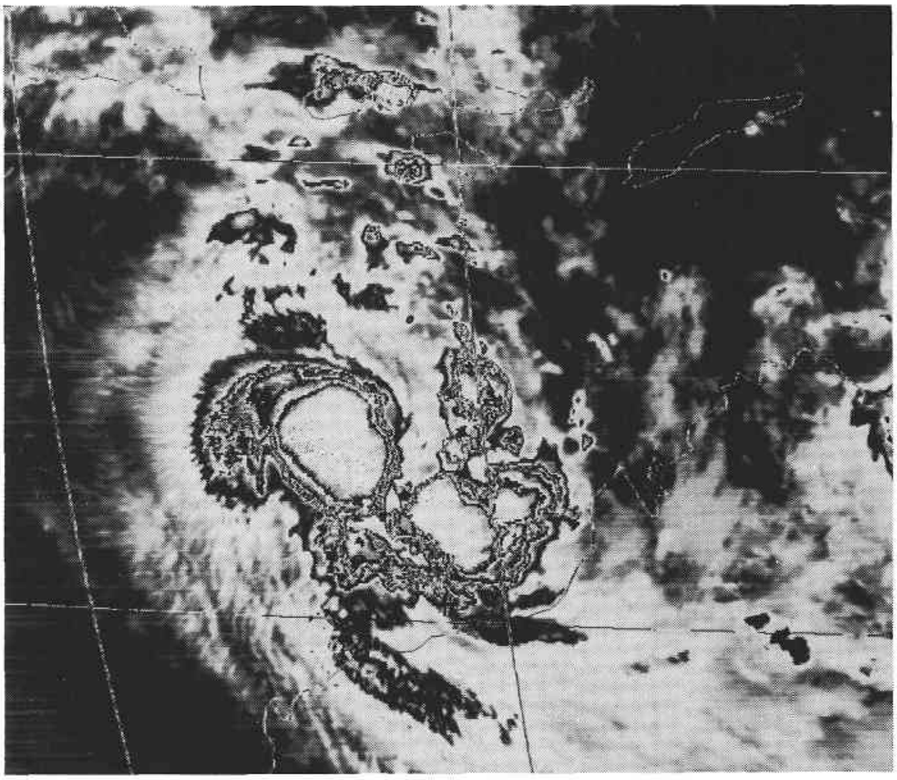
Fig. 3. Nephanalysis and cloud classification for 0000 GMT 5 November 1969. Cloud vortices are stippled, with the solid line indicating zero vorticity. Grid point 'bogus' observations are indicated by closed circles for cyclonic points and open circles for anticyclonic points. Cloud classification is as indicated in Figure 17.

development of a cloud vortex (see Fig. 3). It was applied successfully to a number of forecasts from the November 1969 GARP Basic Data Set.

More recent developments have been, for instance, with the NOAA TIROS Operatonal Vertical Sounder (TOVS) imagery for locating the eyes of tropical cyclones. This is assisted by colour graphics techniques which have been developed to differentiate data from the various wave length channels (see Fig. 4).

W1.4.2 Temperature and Moisture Retrievals

The first attempts in the Centre to obtain temperature profiles from clear column radiances from the Vertical Temperature Profile Radiometer (VTPR) were commenced in 1973 with the receipt of NOAA-2 satellite data from the USA following the work of Smith *et al.* (1970). A series of experiments was conducted



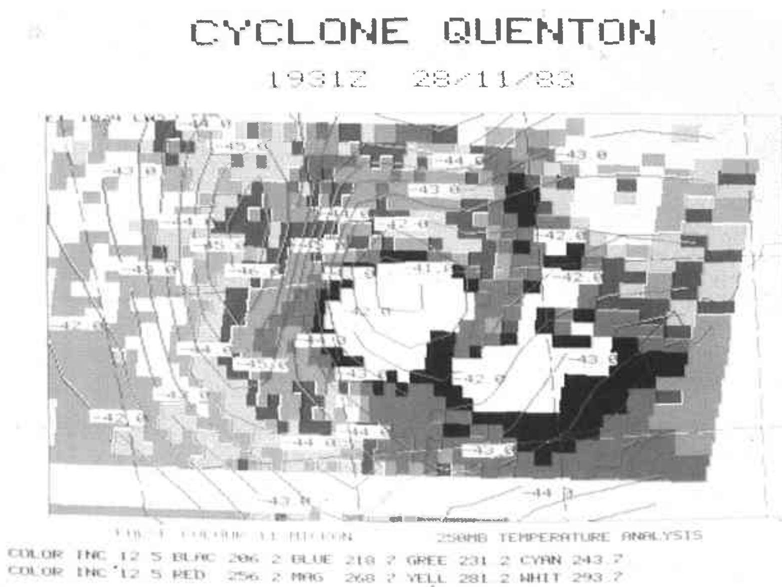


Fig. 4. *GMS 11μm infrared imagery of Cyclone Quenton off the north west Australian coast at 1800 GMT 28 November 1983 (upper) and the false colour image from the NOAA-7 11μm TOVS data at 1931 GMT for the same date with the 250 mb temperature analysis superimposed. The black and white image indicates two clusters of cloud tops which are colder than −65°C. The false colour image shows clearly the warm outflow region above the cyclone eye (250 mb temperature warmer than −41°C) located to the north of one of the cloud clusters.*

to determine the sensitivity of the non-unique radiance transfer equation to various first estimates of temperature and moisture. Some success was obtained by using a numerical prediction model to provide estimates below 100 mb for the NOAA-2 radiance data, while climatology was used above 100 mb.

The technique which has seen greatest development in the Centre, however, has been to determine radiance-temperature relations from a series of linear regression equations between satellite radiances and ground-based radiosonde data. Iterative discriminant analysis is used to group the data 'synoptically'. This approach has resulted in the reduction of both bias and root mean square error for retrievals over the Australian region when compared to those received from the USA. After several data impact assessment tests (see Sections W2.1.3 and W2.2) January 1978 saw the acceptance of the discriminant analysis procedure for the local reduction of VTPR satellite data for operational real time hemispheric analysis by NMAC of the Bureau of Meteorology.

Recent extensions of this work have been the establishment of local readout capabilities for the TOVS data, assisted by algorithms obtained from the University of Wisconsin (UW). Since early 1981 two to three orbits per day over eastern Australia have been processed to yield temperature profiles at a horizontal resolution of down to 60 km within two hours of the satellite pass. This compares with data processed in the USA being received five hours after the satellite pass, at a horizontal resolution of approximately 500 km. With the subsequent establishment of direct readout capability at Perth, Western Australia, there is now full Australian coverage. In addition to higher densities of temperature and moisture information, the locally processed TOVS data yield 1000 — 500 mb geopotential thickness and geostrophic wind shears, and (with the use of a sea level pressure analysis) the 250 mb geopotential height and geostrophic winds (see Fig. 5).

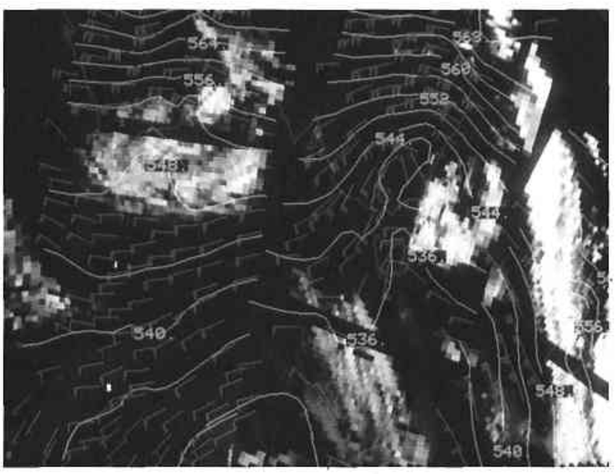


Fig. 5. *11μm window channel imagery from the HIRS-2 instrument on the NOAA-7 polar orbiting satellite for 16 November 1983, with the 1000-500 mb wind shears (knots) and thickness analysis (dm) obtained from the satellite derived temperature data.*

Currently efforts are again being directed towards improving physical retrieval algorithms (Smith *et al.*, 1984), as the regression approach is unable to take account of complex surface conditions, or to utilize a forecast first guess. These developments are now feasible as a result of the recent improvements to the

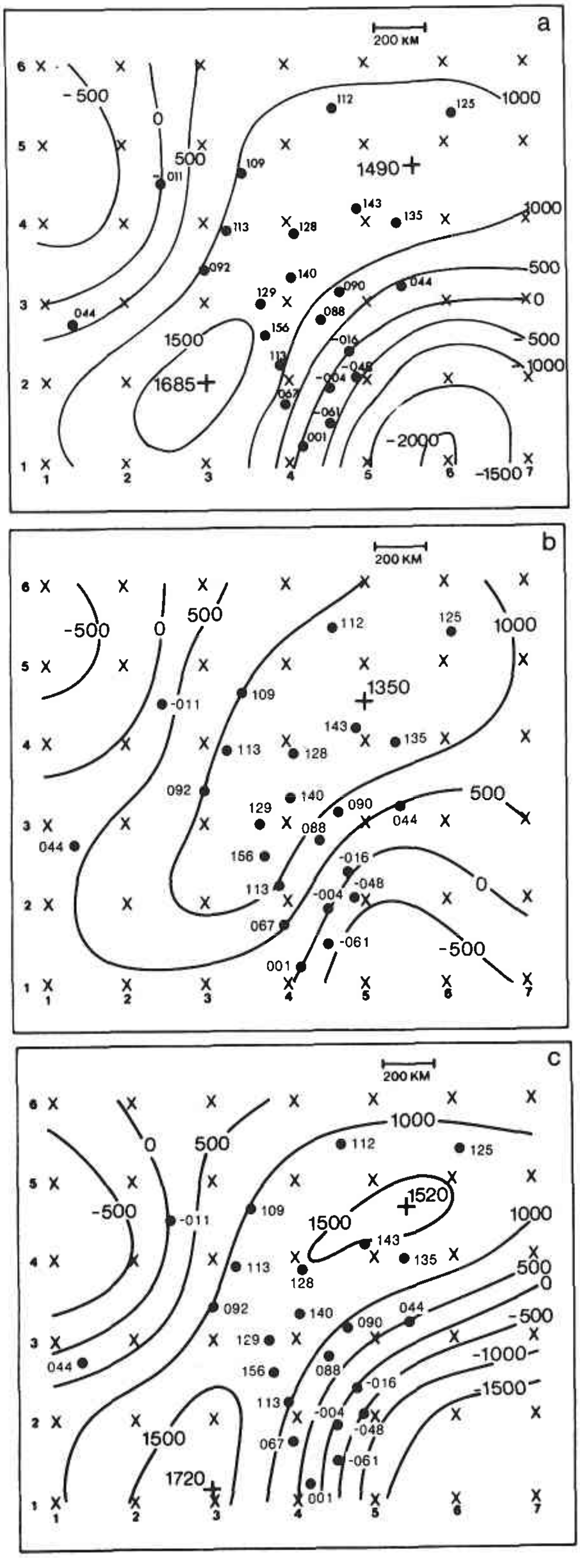


Fig. 6. *Observations (normal increments times 100) and analyses of a synthetic data realisation using statistically optimum weights (a), the best SCM setting (b), and the true field (c).*

Australian region primitive equation (ARPE) model which include improved model physics and initialization, increased vertical and horizontal resolution, and a 'nesting' procedure by which its boundary conditions are obtained from the hemispheric spectral model (see Section W2.2). A surface air temperature and moisture analysis program is being developed for use in conjunction with a direct inversion algorithm recently received from UW and a high resolution topography data set for the Australian region has been modified for use with the TOVS data processing.

W1.5 Observational Networks and Analysis Accuracy

The design of observational networks is an important practical problem. Some of the concepts used in numerical analysis are relevant to observational network design. In particular, the mathematical theory of interpolation may be used to address the question of the analysis accuracy achievable with a specified observational network. This theory provides a quantitative estimate of the root mean square analysis error to be expected at any point in an analysis domain. The analysis error will depend upon many factors, such as network density, observational accuracy, and the characteristic variability in space and time of the element being analysed.

Some examples of practical problems which have been addressed using interpolation theory are:

- the effects of adding, or removing, specified stations from the Australian upper air observing network;
- the effects of reduced observing frequency at specified stations;
- trade off between station density and observing frequency in specified areas;
- disposition of a fixed number of drifting buoys in the Southern and Indian oceans, so as to minimize analysis error.

In addition to specific problems such as the above, interpolation theory has also been used to examine more general problems in a quantitative way. These include:

- the variation of absolute and differential accuracy of analyses, with network density, observational accuracy, and characteristic length scale of the element being analysed;
- the interpolation accuracy and parameter sensitivity of different methods for numerical analysis.

An example of this last study is illustrated by Figure 6 which shows analyses of a particular distribution of synthetic data using statistical interpolation theory, and the successive correction method (SCM) of Cressman compared with the true field.

W2 FORECASTING

Overview

Upon the formation of the CMRC the numerical systems available in the Bureau of Meteorology were an Australian region multi-level analysis scheme (Maine and Seaman, 1967) and an Australian region one-level barotropic prediction model (Maine, 1967). Development was well advanced for operational application of a baroclinic filtered model for the region, and Bureau staff were involved in adapting the US GFDL primitive equations general circulation model for weather forecasting in the southern hemisphere. These initiatives paved the way for numerical weather prediction research in the first years of CMRC/ANMRC. Subsequent research into spectral transform methods, as distinct from the use of finite difference methods, led to the development of baroclinic primitive equation spectral models for research and operational use over the hemisphere by the mid seventies. The burgeoning data base associated with the space-based observing systems of the polar orbiting and geostationary satellites, and the advent of the First GARP Global Experiment (FGGE) in 1979 prompted development of a four dimensional assimilation system within the framework of the spectral model. At the disbandment of the ANMRC this assimilation prediction system has just become operational in the Bureau of Meteorology.

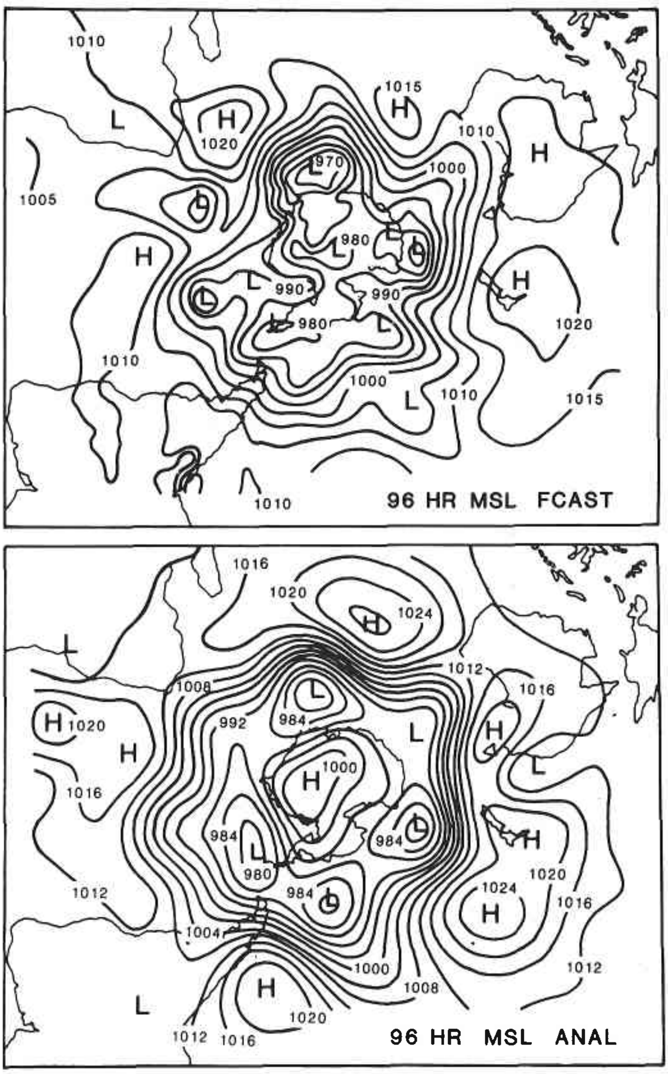


Fig. 7. *Mean sea level pressure prediction 96 h in advance from the six-level PE model with the corresponding verifying analysis during a typical extended range experiment in the early 1970's.*

W2.1 Southern Hemisphere

W2.1.1 Finite Difference Models

The Bureau of Meteorology's requirements for a hemispheric numerical analysis-prediction system were identified in the early 1970's as pressing. In the Centre a filtered baroclinic model, initially developed for the Australian region, was being generalised for southern hemisphere prediction on a 47 × 47 (N23) polar stereographic projection, and a hemispheric grid point primitive equation (PE) model developed at GFDL (Smagorinsky *et al.*, 1965) and made available to the Bureau of Meteorology, was being modified further for comparative assessment. A major experiment with this latter model in 1970 was an assessment of 24 hour predictions based on the November 1969 GARP Basic Data Set, with a 12 hour feedback cycle to the hemispheric analyses. Later, 96 hour predictions were subject to extensive comparisons with manually prepared forecasts (see Fig. 7), and although the initial results were encouraging, analysis uncertainties in data sparse areas of the hemisphere were identified as a major problem. Further effort directed towards this model's operational use was in doubt, however, due to the additional computational overhead of the primitive equations. The filtered model on the other hand, had a clear advantage of computational efficiency with the larger time step permissible. It had demonstrated 24 hour prediction skill equivalent to manual methods at mean sea level, and was slightly superior to manual methods at upper levels.

Despite subsequent improvements in hemispheric analysis and substantial gains in performance by the PE model relative to earlier trials, an optimized version of the filtered baroclinic model incorporating an energetically consistent formulation, was the one finally accepted for operational use in 1972. Thus the major goal of a real time hemispheric analysis-prognosis system had been achieved. The reprogrammed filtered model effectively remained unchanged in Bureau operations until 1976, with seven levels and N30 resolution, but functioning with the lower (N23) resolution analysis.

With a view to increasing the utility of 96 hour predictions, a parallel effort in the early seventies was directed towards improving the physical parameterization of convection and the incorporation of radiative heating into the PE model. The PE model was in fact used to provide guidance to the extended forecasting section of the Bureau for a number of months commencing in late 1972.

Although further improvements in performance and efficiency were obtained with the PE model through semi-implicit integration, the near equivalent performance and superior efficiency of the spectral model (see below) suggested that it become the basis for large scale prediction, and that the PE model continue to be developed for Australian region research.

For much of the subsequent hemispheric research, the inadequacy of the Bureau IBM 360/65 computers became apparent necessitating the acquisition of additional time of the CSIRO CDC 7600 machine.

W2.1.1 The Spectral Model

Research into the use of spherical harmonic representation of dynamic model variables was initiated within six months of the formation of the CMRC prompted by Robert's (1966) application of the spectral method to primitive equation models and the formulation by Merilees (1968) of primitive vorticity and divergence equations. The pioneering studies of Silberman (1954) and Baer and Platzman (1961) pointed the way for spectral models via the use of interaction coefficients, as was implied also in the formulation of Merilees. By mid 1970 a free surface PE model using interaction coefficients had been developed in CMRC and initial tests conducted of semi-implicit time integration and analytic Rossby-Haurwitz wave initialization. At this time Eliasen *et al.* (1970) and Orszag (1970) in a decisive development proposed the use of transform procedures in spectral model integrations, thereby overcoming the principal disadvantages of inefficiency and difficulties with highly non-linear physical processes.

Comparison of the CMRC interaction coefficient free surface model and a newly developed transform version utilizing both primitive vorticity and divergence equations, demonstrated an order of magnitude improvement in efficiency of the latter model at the relatively low resolution of wave number 15 (see Fig. 8). Numerical stability and accuracy, as well as the ease of semi-implicit time integration and global modelling, together with the potential to handle terms more complex than quadratic, were now very clear advantages of the spectral method using the transform approach.

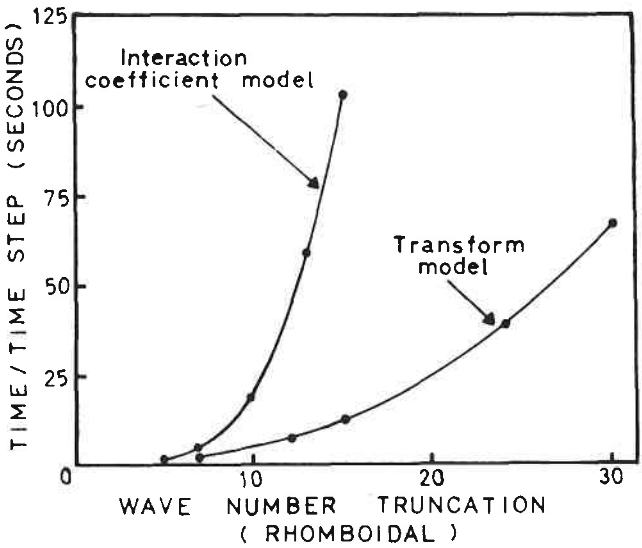


Fig. 8. *Computation time per timestep as a function of spectral resolution for the integration of a global spectral model employing the transform method compared to one employing the interaction coefficient method.*

By mid 1972 the first integrations from real data were performed with an adiabatic baroclinic spectral model, integrated via the semi-implicit algorithm and interfaced with the newly operational southern hemisphere analysis system. In these studies initialization was by direct use of the analysed mass and wind fields, but was later succeeded by a divergence dissipation scheme based on a suggestion of Sadourny (1973). In 1973 experimental 48 hour predictions using the GARP Basic Data Set for November 1969 were compared in detail with those of the operational filtered baroclinic model. The spectral model prognoses proved to be more accurate in phase prediction of synoptic systems and were quantitatively slightly superior. Real time trials in parallel with operations in 1974, demonstrated the suitability of the spectral model to provide both a 12 hour first guess to analysis and a 48 hour prediction over the hemisphere. To meet the demand of operational constraints, the global model was converted to a truly hemispheric version with seven levels in the vertical, and 15 wave numbers; it also included moisture and convection. Concurrently, the spectral model underwent general circulation simulation tests (see Section C1.4.1) which greatly assisted prediction studies through the development of comprehensive physical sensitivity parameterization schemes.

With the addition of topography and land-sea contrast, a six week real time operational trial in 1975 reaffirmed that the spectral model could provide useful guidance up to 48 hours in advance (see Fig. 9). Thus it was finally implemented operationally in January 1976, after 18 months of parallel testing and recoding, replacing the filtered baroclinic model. The Bureau became the first operational user of a baroclinic primitive equation spectral model.

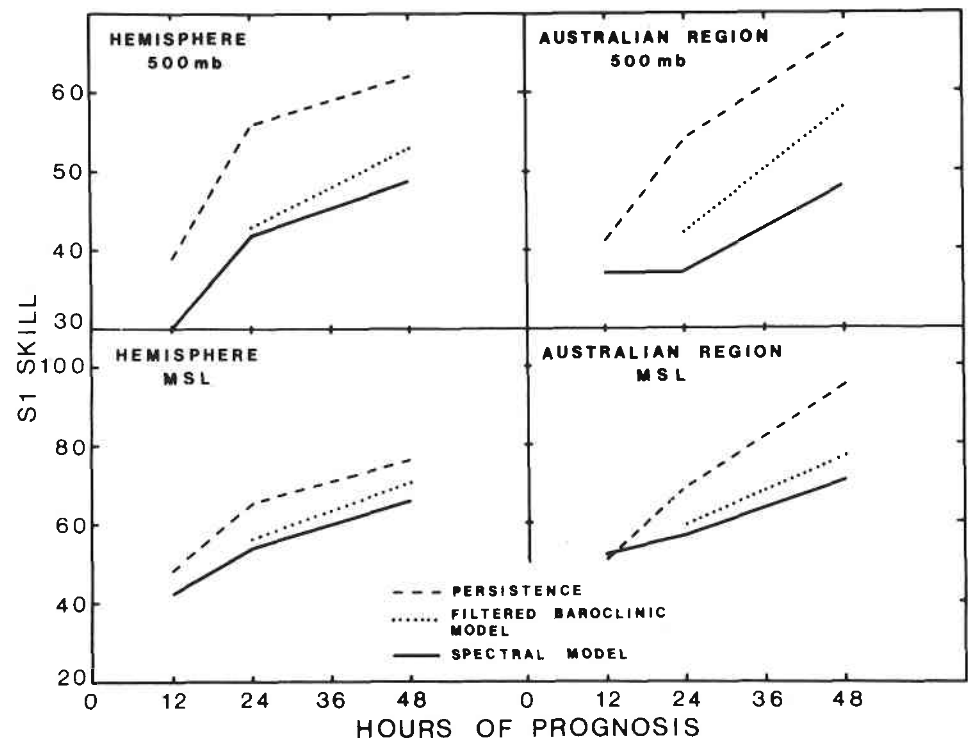


Fig. 9. Mean S1 skill scores averaged for a 24 day period for hemispheric and Australian region prognoses from the filtered baroclinic model and the spectral model. The hemispheric scores were calculated from 20°S to 60°S, and the Australian region scores from 20°S to 45°S, between 110°E and 160°E. Decreasing scores indicate increasing skill.

W2.1.3 Four Dimensional Data Assimilation

To ensure the full utilization of the diverse, inhomogeneous, and vast meteorological data base which was becoming available, particularly in the period leading up to and including FGGE, e.g., the large number of temperature retrievals from polar orbiting satellites, the Centre directed considerable effort towards developing a four dimensional data assimilation scheme. The problem of asynoptic data assimilation was first addressed by the hemispheric PE model in late 1971 using SIRS polar orbiting satellite data from the November GARP Basic Data Set. The requirements for geostrophic correction of the wind field in the presence of temperature data alone and the clear need for a reference level of surface pressure were highlighted in these early studies. In January 1973, the reception of temperature soundings from the USA NOAA/NESS from the NOAA-2 satellite radiance measurements seemed to offer a basis for defining the initial state more accurately for such an assimilation system. However the use of these data operationally was through the conventional synoptic analysis system.

In April 1976 the operational seven-level spectral model was used in experimental trials for one month of analysis-forecast cycling in which the impact of NOAA-4 data was also assessed. The discriminant retrieval method was tested in these experiments which were based on a 12 hour cycle. Manual intervention was confined to the specification of mean sea level pressure once each 24 hours with limited input at the upper levels where no satellite retrievals were available. These experiments demonstrated that this limited manual input coupled with the satellite data were sufficient to maintain a satisfactory analysis-prediction system for the southern hemisphere.

Prompted by the success of this experiment, four dimensional assimilation for use with the spectral model has undergone continuous development up to the present. It was developed around the version of the ANMRC spectral model that had been used for general circulation climate studies (see Section C1.4.1). This approach allowed univariate analysis by the successive correction method of

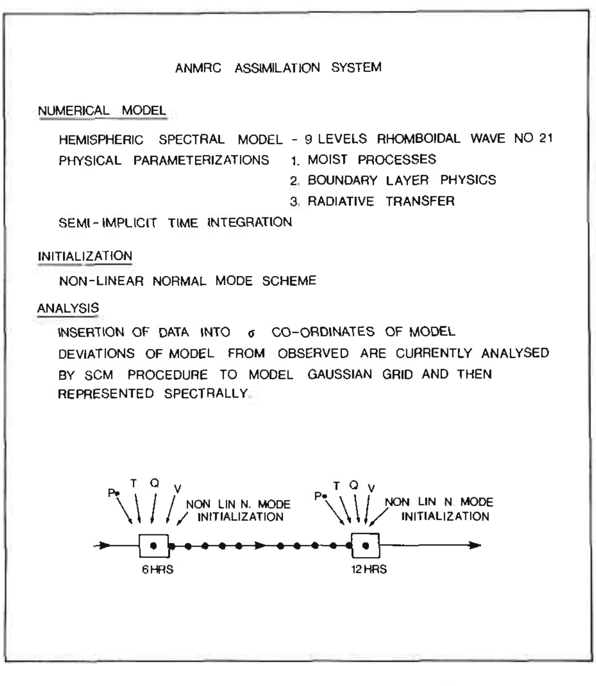


Fig. 10. The principal features of the ANMRC assimilation system.

contemporaneous pressure, temperature, mixing ratio and winds, at any or all time steps of the model (see Fig. 10). Geostrophic corrections were made to mass field changes arising from surface pressure and temperature updates. The availability of objective analysis procedures within the framework of the spectral model, the comprehensive prediction component provided by the model, and finally the inclusion of a non-linear normal mode initialization constituted the basic assimilation system utilized for major experiments with data from the FGGE year. These experiments represented a major Australian effort addressing the primary objectives of GARP, namely to determine the optimum design for a global observing system, and to assess the impact of FGGE data on numerical analysis and prediction. They suggested that the FGGE data base was sufficient to support a data assimilation cycle in the southern hemisphere with manual interaction limited to observational data monitoring and editing.

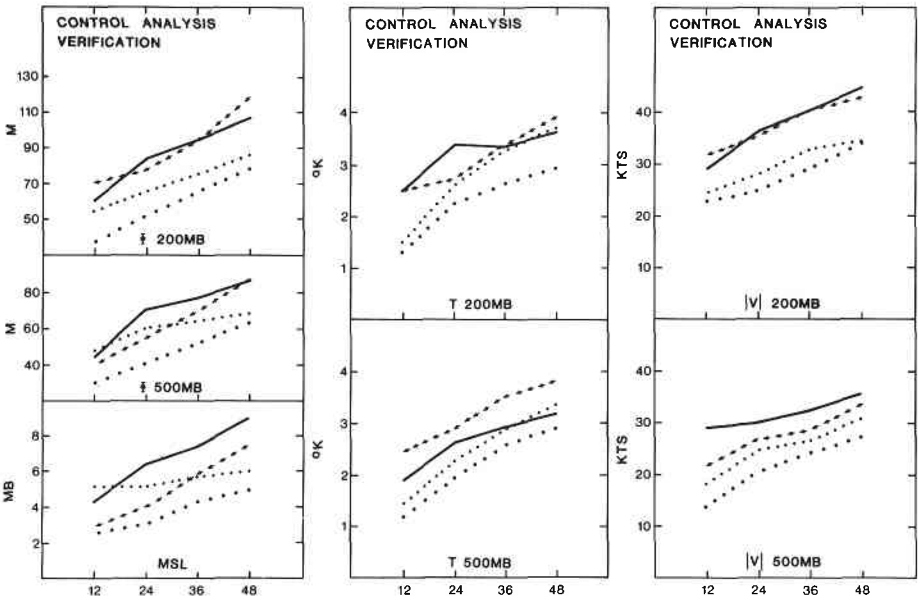


Fig. 11. Root mean square forecast error statistics in the Australian region averaged over three situations and verified against the control analyses for mean sea level pressure, 500 mb and 200 mb geopotential heights (left), for 500 mb and 200 mb temperature (centre), and for wind at the same levels (right). The dotted line denotes the control prognoses, crosses indicate no drifting buoy pressure data included and arrows indicate no satellite temperature retrievals included; the full line indicates persistence.

Thus with the assimilation system established, it was shown that the quality of prediction at 48 hours depended crucially on data from both ocean buoys and satellite temperature soundings (see Fig. 11). The buoys in particular had a positive impact on prediction in the region and the hemisphere, while the satellite soundings showed positive impact at 500 and 200 mb levels as well as at mean sea level. A very powerful component of the assimilation scheme from both a practical and diagnostic view point, is the non-linear normal mode initialization procedure. Detailed studies of its characteristics indicate further potential gains in low latitude analysis and prediction. The introduction of linear initialization, frequency cut-off initialization, and clarification of the role of Kelvin waves in maintaining tropical circulations have been recent studies of particular relevance for large scale analysis and prediction.

With the acquisition of the FACOM M200 computer by the Bureau in 1982 it has been possible to test the potential of the assimilation system for operational use. A substantially enhanced system compared to that used for the FGGE tests, it now utilizes univariate optimum interpolation instead of the successive correction method, and improved model parameterizations for radiative heating and cooling, and turbulent transfer processes in the boundary layer. Relative to existing operations the new assimilation system is much more comprehensive in data usage, and in addition includes a stratospheric analysis. Trials paralleling real time for July and September 1983, and January and June 1984, indicate the equivalence of the new analyses with operational analyses, and an undoubted improvement in the prediction capacity arising from the improved model component (see Fig. 12).

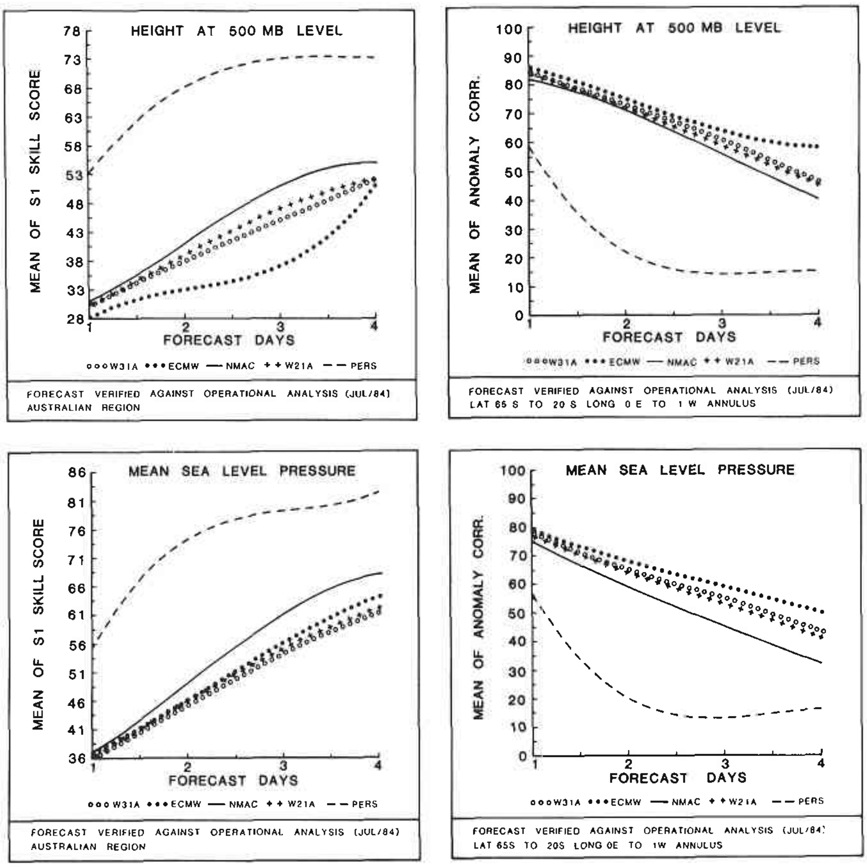


Fig. 12. *Quantitative verification of 20 four day hemispheric forecasts for July 1983 from the ANMRC assimilation system, the Bureau of Meteorology operational system denoted by NMAC (which utilizes the ANMRC W21, nine-level spectral model for prediction from the Bureau's operational hemispheric analysis), and from the European Centre for Medium Range Weather Forecasts (ECMWF) operational model. Verifications for the Australian region are shown on the left, and those for a southern hemisphere annulus in terms of anomaly correlation coefficient on the right. W21A and W31A denote wave number 21 and 31 rhomboidal truncations respectively, each with nine levels; PERS denotes persistence.*

W2.2 Australian Region

At the time of establishment of the CMRC, forecasts of the 500 mb height fields up to 24 hours in advance were being obtained in the Bureau of Meteorology from a barotropic filtered model. This model was succeeded by a seven-level filtered baroclinic model in 1970 which had also been developed prior to the formation of CMRC. It was replaced by an improved version in 1972 which remained operational until September 1977. However it was anticipated in the early seventies that a PE model would be beneficial, and initial experiments to develop such a model based on the southern hemisphere version commenced in the Centre in 1971.

At this stage PE models were not competitive because of the severe restrictions imposed on the maximum time step allowable by the fast moving gravity waves. The semi-implicit time differencing procedure of Robert (1969) held hopes for surmounting this drawback, so that by 1974 the hemispheric finite difference model had been converted to a semi-implicit formulation and recast over the Australian region. This Australian region primitive equation (ARPE) model which includes the immediately adjacent waters operated at a resolution of approximately 250 km with six levels in the vertical. Use of a staggered space grid formulation also gave significant gains in efficiency. By late 1976 this model was tested extensively on the Bureau IBM machines by NMAC before it became operational in September 1977, replacing the filtered baroclinic model. Monitoring the ARPE model performance over subsequent months showed that the average monthly S1 skill scores for a numerical weather prediction model were superior to those for manually produced mean sea level forecasts for the first time in the Australian region.

One subsequent change to this operational version has been the introduction of a 'nesting' procedure in 1981 enabling the forecast period to be extended to 36 hours; the regional boundary conditions are obtained from a 48 hour spectral model calculation initiated at the analysis time 12 hours prior. The other significant improvement to the ARPE model has been the introduction of a non-linear vertical mode initialization scheme. The linearized equations with respect to which the model modes are defined admit only gravity modes, and this approach has been found to be effective in controlling spurious model oscillations. These changes are indicated in Figure 13 together with the operational mean monthly S1 skill scores for the Australian region for the period 1970 to 1984.

With access to CSIRO's CYBER 76 computer, in 1976 a ten-level version of the ARPE model was used to assess the impact of Nimbus-6 satellite temperature retrievals obtained from data made available to the Centre from NOAA NESS in the USA. As well as high resolution infrared data, information was available from the microwave soundings in cloudy as well as clear areas of the atmosphere yielding high resolution (approximately 125 km) retrievals for the Australian region. Two series of analysis-forecast cycling experiments were performed where the model prediction at six hours provided a guess field for newly available data. One series used conventional data only, and the second used satellite derived thickness and temperature information. The 24 hour predictions from the second series showed a marked improvement in accuracy at all levels compared to the first, with a significant reduction in human effort required; manual intervention was necessary only at the surface.

TABLE 1

Comparative S_1 skill score performance at mean sea level of the operational ARPE model in 1978 and 1979 relative to persistence. TIROS–N and drifting buoy data were available in 1979. Scores marked* are record low values for that month.

MONTH	PERSISTENCE 1978	PERSISTENCE 1979	OPERATIONAL MODEL 1978	OPERATIONAL MODEL 1979
January	57	56	49	47*
February	61	55	49	48
March	56	65	47	49
April	56	63	49	47
May	54	56	43*	45
June	61	53	51	42*
July	61	57	48	42*
August	59	62	44	42*
September	68	57	50	44*
October	55	61	42*	43
November	57	63	48	47*
December	58	59	49	46*
Mean	59	59	48	45

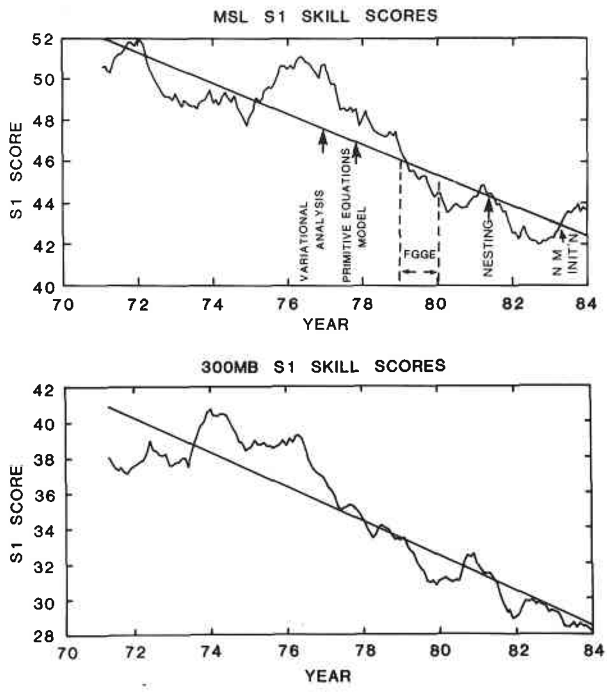


Fig. 13. Variation with time of the filtered (running 12 month mean) operational mean monthly S1 skill scores for the Australian region numerical prognoses for mean sea level pressure and 300 mb geopotential height. The approximate times of the major improvements to the operational system are indicated.

Another project of significance, conducted jointly with the UW in 1978–79 was designed to assess the impact on numerical weather prediction of high resolution temperature profiles. These were produced by UW from satellite radiance data using the Man Computer Interactive Data Access System (McIDAS). Sixty kilometre resolution versions of the Australian region objective analysis and forecasting models were constructed and adapted to operate over the North American region. Tests of this system on a number of cases using the UW data sets, and also with conventional data showed that forecasts comparable to the US limited area forecasting model could be obtained.

More recently an extensive series of experiments has been carried out using the FGGE data over the Australian region. Almost certainly due to this enhanced data base, particularly the improved satellite data and drifting buoys over the Southern Ocean, seven record low monthly S1 skill scores were obtained in 1979 by the operational ARPE model (see Table 1 and Fig. 13). The mean daily improvement was of the order of three skill score points at all levels.

Although manual analysis has been an essential component of the operational analysis system since its inception, the enhanced data base during FGGE provided the opportunity to assess whether an objective analysis-forecast system would be feasible with manual intervention limited to a preliminary data checking phase. Using a six hour analysis-forecast cycling mode for nine days during the FGGE Special Observing Period 2 (SOP-2), this scheme remained stable (see Fig. 14). A 24 hour forecast computed each 12 hours, to measure the effect of the experimental analysis on predictions, indicated that the SOP-2 data sets were sufficient to support such a system.

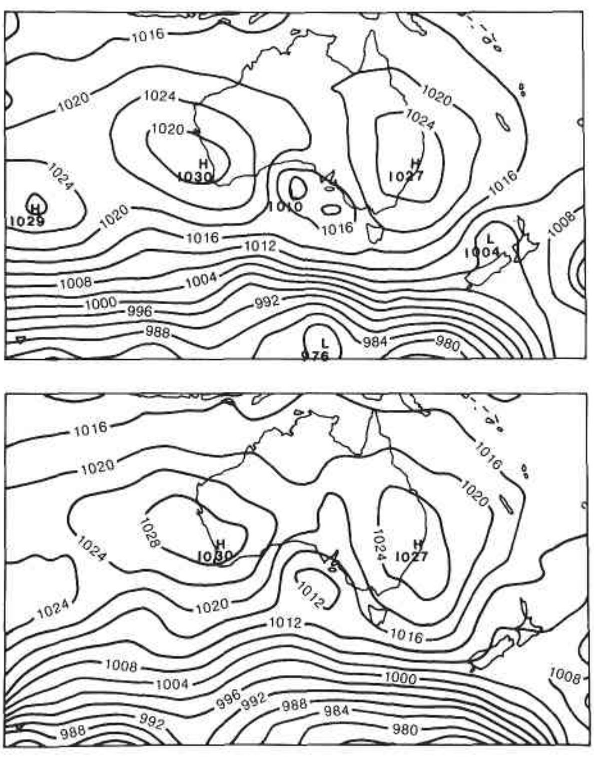


Fig. 14. Mean sea level pressure analyses for 0000 GMT 26 May 1979. The operational analysis is shown in the upper section, and the equivalent analysis produced after nine days of automated analysis-forecast cycling using the ARPE model in the lower.

W2.3 Mesoscale

W2.3.1 Moveable Fine Mesh (MFM) Model

The development of a MFM model commenced in 1979, the primary aim being to study mesoscale phenomena. This required much higher model resolution than available from other NWP models in the Centre. The MFM model constructed operates with variable resolution within the ARPE model and is capable of 'following' discrete atmospheric phenomena. It has been applied to a number of mesoscale weather events, the principal one being the simulation of 'southerly busters' which occur along the New South Wales coast about 20 to 30 times per year, mainly in spring and summer. For the eight situations examined to date, there has been good agreement between model forecasts, for resolutions of 60 km and 30 km, and verifying analyses (see Fig. 15). Other applications have been to a cold front situation, and to a rare rainfall situation over south west Western Australia.

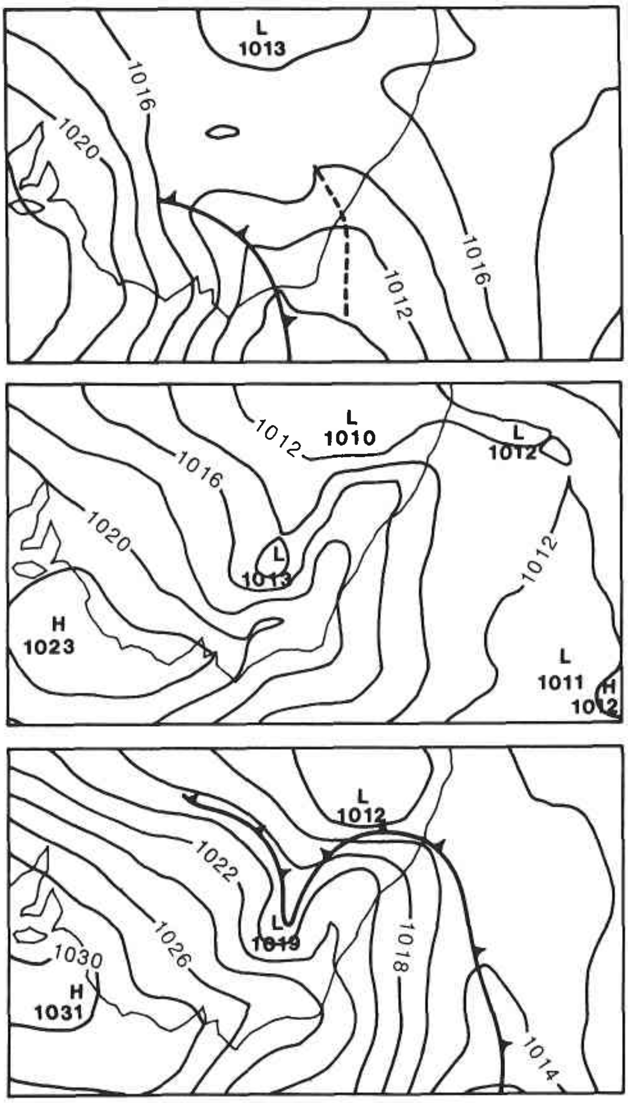


Fig. 15. The manual mean sea level pressure analysis for 1100 GMT 24 October 1972 (upper), constituting the initial state for the 24th mean sea level pressure prognosis from the ANMRC MFM model (centre). The verifying analysis is shown in the lower section of the diagram.

W2.3.2 Australian Nowcasting System

This system has evolved during 1982 to 1984 from the Australian region analysis-forecasting system (Section W2.2), the use of TOVS data (Section W1.4.2) and the development of the MFM model above. It consists of three principal modules, namely the Australian meteorological data base, the data assimilation-forecasting system, and the meteorological interactive display system. To meet operational requirements of the Bureau of Meteorology, the regional prediction model has been restructured so that it resides fully in the computer memory; it is scheduled to become the next operational regional model. This 'new' model utilizes variational analysis, the TOVS retrieval package, 'external nesting' to the operational hemispheric spectral model for its boundary conditions and 'internal nesting' to a finer mesh to focus on discrete phenomena. It also features a high resolution surface temperature analysis, variable resolution (currently set at 100 km), and vertical mode initialization. The fine mesh (down to 30 km) forecasting capability will constitute the nowcasting component of the system. At present (August 1984) the regional prediction model is undergoing operational trials within the Bureau, while the data assimilation-forecasting system is being developed for research purposes and future operational nowcasting.

W2.3.3 Monash Collaborative Studies

An extensive series of numerical modelling experiments has been carried out jointly with the Monash University Geophysical Fluid Dynamics Laboratory over the period 1970 to1981. These projects can be divided conveniently into three groups.

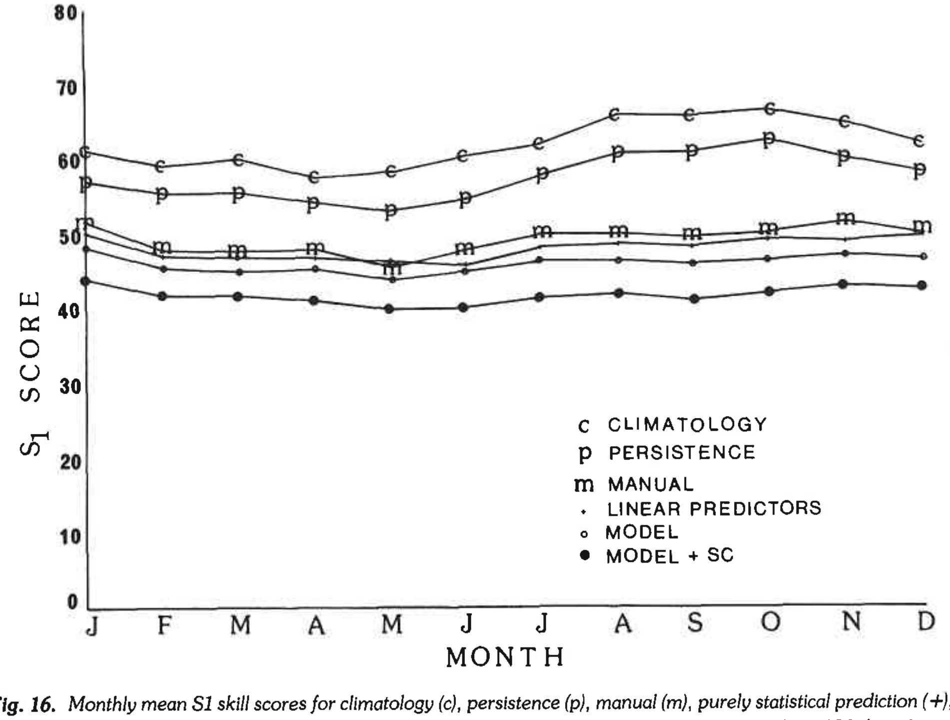


Fig. 16. Monthly mean S1 skill scores for climatology (c), persistence (p), manual (m), purely statistical prediction (+), model (o), and statistical corrected model prognosis (●). Each calendar month is represented by about 180 days during the period 1972 to 1977.

Correction of Dynamical (NWP) Models: A statistical scheme has been devised, in collaboration with Monash University, for identifying and reducing systematic biases in the operational ARPE model. The essential feature of the scheme is that the model prognosis and analysis are used to predict the model **error**, rather than the full field. (The latter leads to unrealistically smooth fields.) The final forecast and the error correction thus still retain the small scale structure predicted by the dynamics alone. Results indicate that reductions in S1 skill scores of approximately three points could be obtained in the mean sea level pressure field forecast to 24 hours (see Fig. 16). In addition empirical Bayes' methods have been used to construct decision rules for the application of the correction scheme only when prognoses would be improved. This leads to further potential gains in skill for the operational ARPE model.

Local Wind Systems: A numerical model was constructed for the investigation of a range of mesoscale wind circulations. These included sea-land breezes; katabatic winds produced by nocturnal cooling of an isolated hill; the plume and inflow region of a fire generated wind storm; heat island induced circulations; and the genesis and development of 'dust devils'.

Tornadoes: The extreme violence of tornadoes, their short life-span and small scale, until recently has severely restricted the collection of relevant data, which in turn has hampered the understanding of their formation and behaviour. The recent development of Doppler radar and observational efforts in the USA has alleviated this situation to some extent. ANMRC modelling research with Monash University was the first to utilize two pre-requisite conditions for tornado genesis, namely an upward driving force (convection in the parent cloud) together with an organized source of rotation (supplied by the meso-cyclone). Not only did this model produce a tornadic vortex, but also it explained how a tornado develops downwards. Using observed magnitudes of other parameters, features such as core size and vortex strength were also reproduced successfully. Explanations have been found for why so few storms actually spawn tornadoes, and why not all tornadic vortices reach ground level. By including observed vertical soundings of temperature and moisture, the distribution and level of buoyancy was shown to account for the formation and maintenance of an intense tornado when the level of background cyclonic rotation was within the observed range of values.

TABLE 2

Probability of occurrence of rain in Melbourne during winter in the next **12 hours** as a function of the current observed state and the state three hours prior. States 1, 2, 3 are cloud amounts of 0-2/8, 3/8-5/8 and 6/8-8/8, respectively with 4 the rain state.

		Past State			
		1	**2**	**3**	**4**
Current State	1	0.05	0.07	0.10	0.12
	2	0.22	0.25	0.27	0.30
	3	0.30	0.33	0.37	0.41
	4	0.57	0.62	0.67	0.73

W2.3.3 Statistical Forecasting of Weather Elements

In collaboration with CSIRO Division of Mathematics and Statistics probabilities for rain and cloud amount have been forecast for up to 12 hours in advance by fitting a second order Markov Chain model to three hourly data. The model, which has time-of-day dependent transition probabilities, has been applied to five major Australian cities, with the forecasts appreciably exceeding persistence or climatology. One major advantage over other schemes, e.g., model output statistics (MOS), is that once the transition probability tables have been established, a forecast can be made immediately the observation is available. In the example shown in Table 2, if it was clear at 0900 and clear at the current time of 1200, then the probability of rain in the next 12 hours is 0.05.

References

BAER, F. and G.W. PLATZMAN (1961). A procedure for numerical integration of the spectral vorticity equation. **J. Meteorol.**, 18: 393–401.

ELIASEN, E., B. MACHENHAUER and E. RASMUSSEN (1970). On a numerical method for integration of the hydrodynamical equations with a spectral representation of the horizontal fields. Institute of Theoretical Meteorology, University of Copenhagen, Report No. 2.

MAINE, R. (1967). Experiments with the barotropic model in the Australian region. **Aust. Met. Mag.**, 15: 169–189.

MAINE, R. and R.S. SEAMAN (1967). Developments for an operational automatic weather analysis system in the Australian region. **Aust. Met. Mag.**, 15: 13–31.

MERILEES, P.E. (1968). The equations of motion in spectral form. **J. Atmos. Sci.**, 25: 736–743.

NAGLE, R.E. and C.M. HAYDEN (1971). The use of satellite observed cloud patterns in northern hemisphere 500 mb numerical analysis. NOAA Tech. Rep. NESS 55, 255 pp. [NTIS COM–73–50262].

ORSZAG, S.A. (1970). Transform method for calculation of vector coupled sums: Application to the spectral form of the vorticity equation. **J. Atmos. Sci.**, 27: 890–895.

ROBERT, A.J. (1966). The integration of a low order spectral form of the primitive meteorological equations. **J. Meteor. Soc.**, Ser. 2, 44: 237–245.

ROBERT, A.J. (1969). Integration of a spectral model of the atmosphere by the implicit method. Proc. WMO/IUGG Symposium on Numerical Weather Prediction, Tokyo, 26 November-4 December 1969. Japan Meteorological Agency, Tokyo.

SADOURNY, R. (1973). Forced geostrophic adjustment in large scale flow. (Unpublished.)

SILBERMAN, I. (1954). Planetary waves in the atmosphere. **J. Meteorol.**, 11: 27–34.

SMAGORINSKY, J., S. MANABE and J.L. HOLLOWAY (1965). Numerical results from a nine-level general circulation model of the atmosphere. **Mon. Wea. Rev.**, 93: 727–768.

SMITH, W.L., H.M. WOOLF and W.J. JACOB (1970). A regression method for obtaining real-time temperature and geopotential height profiles from satellite spectrometer measurements and its application to Nimbus 3 "SIRS" observations. **Mon. Wea. Rev.**, 98: 582–603.

SMITH, W.L., H.M. WOOLF, C.M. HAYDEN, A.J. SCHREINER and J.F. LE MARSHALL (1984). The physical retrieval TOVS export package. The Technical Proceedings of the First International TOVS Study Conference, Igls, Austria, 29 August-2 September 1983, W.P. Menzel, ed.; A report from the CMISS, Space Science Engineering Center, University of Wisconsin.

2. OBSERVATIONAL AND DIAGNOSTIC STUDIES

Much of the Centre's early research effort was devoted to the adaptation of existing numerical models and the development of new numerical techniques for solving the hydrodynamic equations on the globe. At the same time it was appreciated that:

- our knowledge of the physical processes occurring in the **real** atmosphere was incomplete, especially with regard to the climate of the southern hemisphere;
- it was difficult, in running a numerical model, to trace the lack of similitude of the model to inadequacies in the numerical techniques or the specification of physical processes.

It was therefore recognised that diagnostic studies of the real atmosphere and intercomparisons with models were required to lead to improvements in the model atmospheric simulations. These studies have covered spatial scales from the synoptic to hemispheric, latitude bands from the equatorial to the polar regions and time scales from single days to decades.

D1 SATELLITE DERIVED ANALYSIS AND CLIMATE INFORMATION

Satellite derived cloud picture mosaics for the entire earth first became available on an operational basis in early 1967. These constituted then a unique source of data for the southern hemisphere oceans which were generally without conventional observations. From the establishment of CMRC it was apparent that work should be carried out to utilize these data, first to assist in providing information to be used in day to day analyses, and secondly to derive inferences in relation to broadscale circulation features. Study initially centred on the establishment of a classification system for cloud vortices which are among the more prominent features of the imagery, and which represented different development stages of extratropical depressions (see Fig. 17). The life cycles of such vortices were examined in some detail in relation to the available conventional observations at the same time enabling the derivation of a series of mean three dimensional anomaly patterns of surface pressure and upper level geopotential of 'pseudo observations' for use in day to day analyses (see Section W1.4.1, Fig. 3).

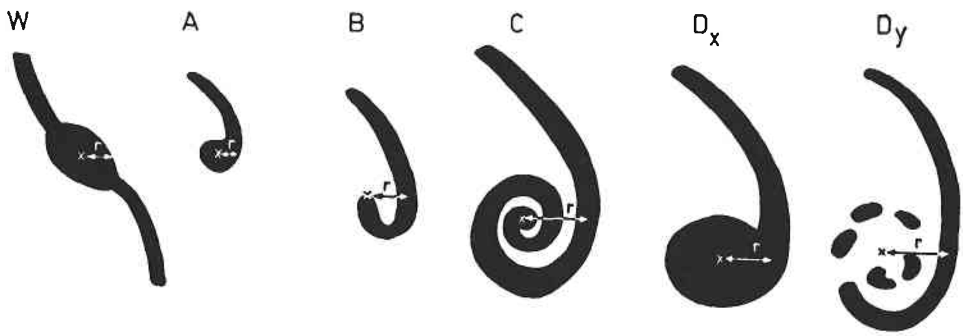


Fig. 17. Schematic diagram of the classification of extra tropical vortex evolution patterns; r is the distance taken as the vortex radius.

W – wave development
A – early vortex development
B – late vortex development
C – full maturity
D – decay: Dx – considerable cloud near the centre
Dy – fragmentary cloud near the centre

A synoptic climatology of these vortex types was produced for the hemisphere and showed time sequences and patterns of evolution, preferred regions of initial cyclonic development and subsequent decay, frequency of tracks and rates of motion. Much of this work confirmed and elaborated on the limited studies that had been made previously using the conventional data of the International Geophysical Year (IGY) of 1957–58. Figure 18 shows an example of a comparison of data derived from these two sources.

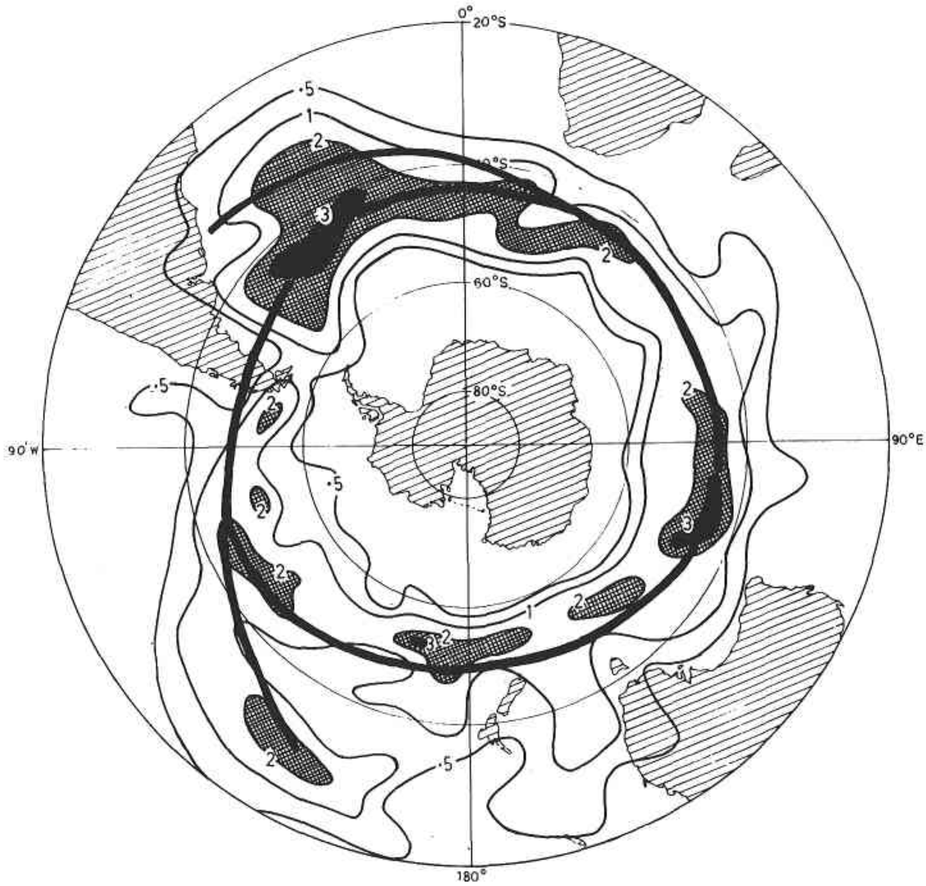


Fig. 18. Frequency of vortices (types W, A and B, see Fig. 17) in summer per unit block (5° latitude by 10° longitude standardized to 45° latitude) per person (December to March) obtained from satellite imagery. The full line is the position of the polar front in summer from IGY data (Taljaard, 1968).

Mosaics of hemispheric cloud cover averaged over periods of several days to several weeks were studied, enabling the identification of persisting cloud bands extending from low to high latitudes which tend to occur with high frequency at particular longitudes. These were related to preferred long wave trough and ridge locations in the atmospheric flow and to the relative frequency of particular wave numbers.

D2 SYNOPTIC AND MESOSCALE FEATURES

D2.1 Observation Based Studies

Because much of the weather over southern Australia occurs in association with extratropical cyclones and fronts, these features became a natural focus for early diagnostic studies. The advent of high resolution imagery from polar orbiting satellites and the Geostationary Meteorological Satellite (GMS) launched by Japan in 1977, greatly enhanced the diagnostic tools available to the research meteorologist in the late seventies. A number of cyclone-frontal related events in eastern Australia was studied during this period. These events were selected so that the satellite data obtained were suitably augmented by the best available surface network. By special arrangement with the Japan Meteorological Agency (JMA), hourly imagery from the GMS were obtained which enabled synoptic and mesoscale cloud features to be observed in unprecedented detail. As well as demonstrating the importance of mesoscale processes in severe weather events, the results of these studies also highlighted the potential advantages of an interactive computer based system for integrating radar, satellite and conventional data for short term forecasting applications in the Australian region. The experience gained also proved to be valuable in the planning and implementation of the first field phase of the Australian Cold Fronts Research Program in 1980.

In 1979, the diagnostic utility of GMS imagery and cloud-tracer winds was demonstrated further in a study of the north west Australian cloudband, a synoptic scale feature frequently important to winter rainfall in central and south eastern Australia (see Fig. 19). As well as providing an improved understanding of the

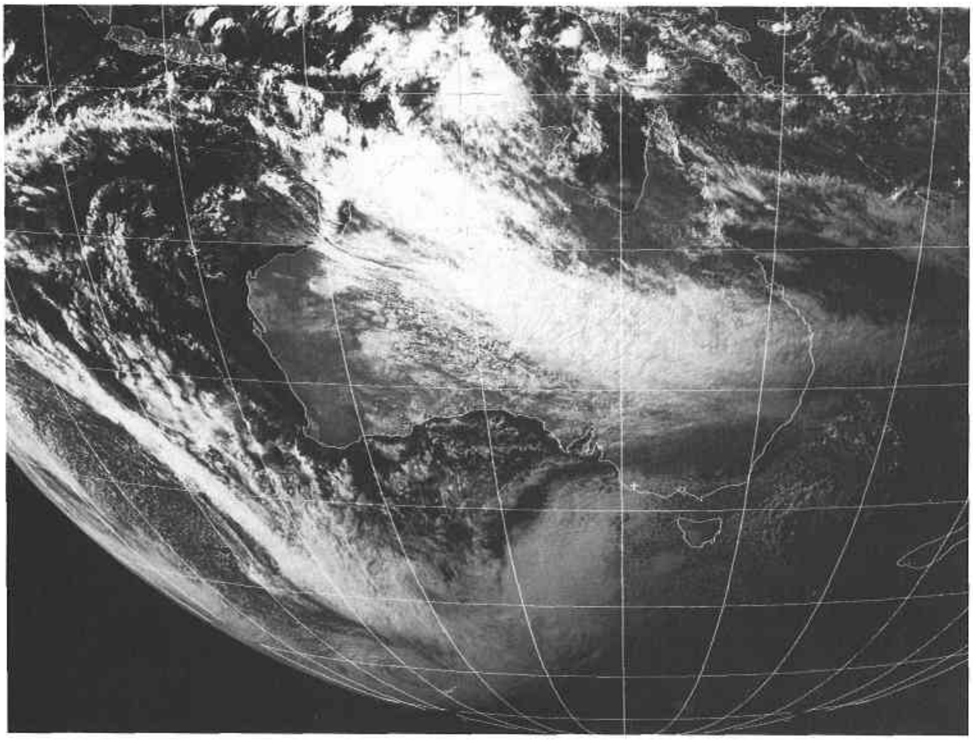


Fig. 19. *GMS-1 visible imagery of the north west Australian cloud band occurring at 0600 GMT 13 May 1979.*

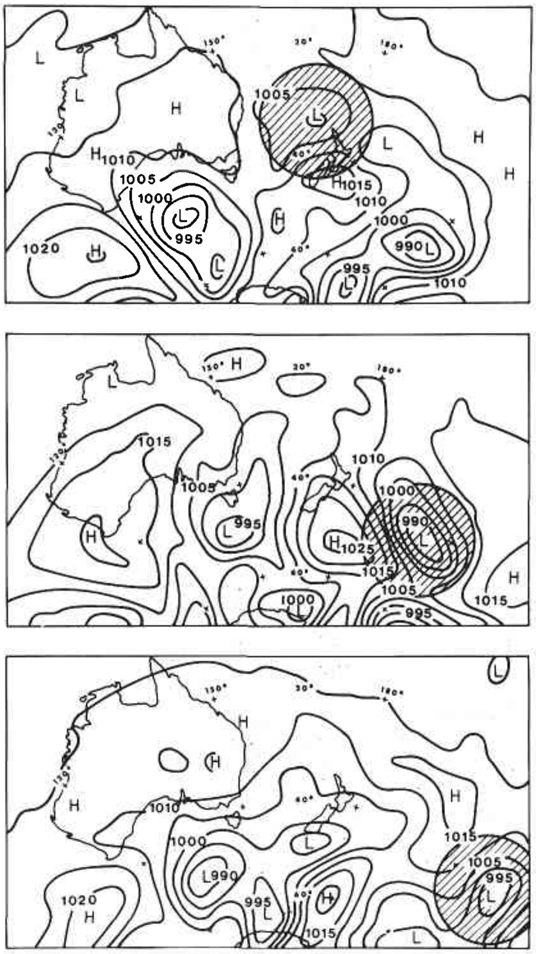
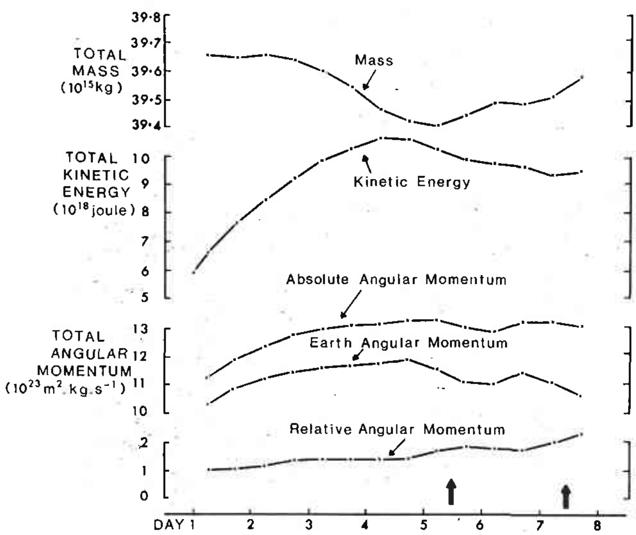


Fig. 20. (a) Mean sea level pressure distribution for a model generated cyclone: Day 1 (upper), Day 4 (centre) and Day 8 (lower). Stippling denotes the area centred on the cyclone, radius 10° latitude, used to calculate the budget quantities in (b).
(b) Temporal distribution of total mass, kinetic energy and angular momentum of the cyclone shown in (a). Arrows indicate periods of fragmentation of the surface centre and/or secondary development.



dynamics of the cloudband, the study also resulted in the first published evaluation of cloud-tracer winds in the Australian region. The data used in these studies were collected during SOP-2 of FGGE and the research was undertaken in collaboration with a visiting scientist from the JMA.

A number of diagnostic studies has also been important in documenting tropical weather systems and formulating hypotheses to explain their behaviour. These have included the onset of the Australian monsoon, pointing to a trigger mechanism in the southern hemisphere rather than a cross equatorial link; active and break phases in the north west monsoon, indicating a relationship with the south east trade winds over the Indian Ocean; rain-producing weather systems in the tropics; and a systematic documentation of tropical cyclones, in particular the accompanying synoptic conditions.

D2.2 Synoptic Systems from Numerical Models

Budget studies of mass, angular momentum and energy constitute an important diagnostic tool for studying the processes involved in the evolution of model generated synoptic systems. In collaboration with researchers at the University of Wisconsin, transport equations were formulated in a framework which moves with the synoptic scale system under study. In this way the exchange of mass, momentum, moisture and energy between the system and its environment can be studied in relation to the sources and sinks of these properties within the system.

Application of this technique to both model generated systems and real systems has proved to be important not only in identifying model weaknesses, but also in providing insight into the physical interactions associated with the evolution of features that occur in the real world. For example budget analyses of two model extra-tropical cyclones one of which is illustrated by Figure 20, showed similar energetics characteristics with the exception of the upper troposphere. This was largely ascribed to the different relative locations of the surface cyclones and their larger scale upper waves. The rates of change of the total kinetic energy budgets, in contrast to those of absolute angular momentum, were not uniquely related to the cyclones' development or decay. Similar analysis of a model anticyclone to a large extent shows it to be a mirrored corollary of the extra tropical cyclones. However, the eddy mode of lateral transport in the upper troposphere was not enhanced by lower level frontogenetic effects as was the case with the model cyclones.

Utilization of the four dimensional internal consistency of the data contained in a model simulation also removes some of the uncertainties of measurement which occur in direct observational studies. Such studies can contribute *inter alia* to a better understanding of the importance of horizontal resolution and sub grid scale processes in simulating synoptic scale systems. For instance a number of features associated with a model retained baroclinic zone was diagnosed based on the ARPE model output for a situation when severe wind damage occurred at a number of locations in south eastern Australia. The diagnostics were undertaken some nine hours into the integration when the three dimensional structure would have become established, and where error growth due to inadequate model physics and resolution might be expected to be reasonably bounded. The results indicated that such short period integrations have the potential to provide a useful base for diagnosing three dimensional structure and the role of various terms in the local energy and vorticity budgets, as well as for developing short term objective forecasting aids, e.g., parameters to assist in estimating potential severe wind damage.

D3 SOUTHERN HEMISPHERE CIRCULATION

D3.1 Observational Climatology

As numerous theories began to appear on the various potential influences on climate, it became increasingly apparent that a continuing historical record was necessary which described the month to month variations in the principal features of the hemispheric circulation. Such a series of descriptions in the form of indices of *inter alia,* latitude of the axis of sub tropical high pressure, latitude of the Antarctic trough, strength of the mid latitude westerlies, and locations of mean centres of high and low pressure may be used to monitor year to year changes and also to assess the degree to which various numerical general circulation model formulations were able to reproduce features of the real atmosphere. Such a series of indices was commenced from the year 1972 using the daily numerical analysis of the southern hemisphere at mean sea level, and data averaged for the five year period 1972 to 1976 were used to derive preliminary means and extremes of the principal characteristics of the circulation. Over the oceans of most of the southern hemisphere the atmosphere was quite barotropic and sea level patterns were indicative of much of the lower troposphere. The mean pattern of surface flow, however, is only one item in the description of seasonal climate, but given the limited data network it is believed to be the most reliable and significant from a human viewpoint.

These indices, which have subsequently been extended for a ten year data set, were used to compare the hemispheric circulations during a transition from extremes of a Southern Oscillation — El Nino cycle in 1972–73, including the substantial changes which occur at middle and high latitudes as well as in the tropics during these events. Changes in the mean pattern were small but fairly well defined, those in the subtropics being associated with the reversal of the Southern Oscillation Index between the two years.

Together with observational evidence from selected pairs of stations, another application of these indices has been to study the broad scale circulation during the FGGE year, revealing its quite anomalous nature. In particular the annual average zonal westerly circulation between 40°S and 60°S was some 18 per cent stronger than the five year index. The FGGE winter was marked by a substantial southward movement of the subtropical high pressure belt and an expansion in its area, particularly in eastern longitudes.

The energetics of the hemispheric circulation during FGGE were also calculated and compared with calculations for earlier data. The FGGE year results differed from the climatological values, having pronounced increases in the zonal energies during some winter months. However, the differences between the two estimates of the southern hemisphere energetics were small compared to differences between estimates for the two hemispheres.

D3.2 Numerical Analysis Climatology

A joint project involving the Bureau of Meteorology and Monash University Department of Mathematics was commenced in 1982 to generate an atmospheric climatology of the southern hemisphere based on ten years of daily hemispheric numerical analyses prepared by NMAC.

The climatology has been compared to the earlier southern hemisphere climatology of Taljaard *et al.* (1969). The major features are that the circumpolar pressure trough is deeper but warmer in the later climatology except in the Drake Passage region. The mean daily standard deviation shows an area of maximum atmospheric variability in a band near 55°S, with local maxima south east of the three major land masses.

Other aspects of the climatology have been examined. A standing wave climatology has been obtained from the ten year means and compared to the earlier climatology. The interannual variability of the monthly means and standard deviations over the ten year period is being studied.

The data manipulation system set up to generate the southern hemisphere climatology is being used to produce southern hemisphere climate diagnostics in real time. At the end of each month, monthly means, daily standard deviations and monthly mean anomalies from the climatology are computed for all the analysis variables.

D3.3 Spatial and Temporal Variability

Most quantitative climatological studies of observed atmospheric mass and motion fields have focused upon the mean properties, variances about the mean, and various conventional general circulation measures such as mean and eddy partitioned fluxes and energies. The aspects of spatial and temporal variability have been studied most commonly by means of spectral analysis. The spectral approach is well suited to gridded data in a global or hemispheric domain, but is less appropriate for irregularly spaced data and limited geographical areas. Work performed in the Centre has therefore utilized an alternative representation of space-time variations, namely the autocovariance function (or equivalently, the local variance and autocorrelation function).

Apart from its value as another index of atmospheric behaviour, a systematic description of space-time autocovariance is useful for practical application in objective analysis, network design, validation of observed data, and forecasting by statistical methods. These practical applications were a significant motivation for doing the work.

The data base used has been the Australian radiosonde and upper wind network. The elements were wind, temperature and geopotential. Variations have been considered for horizontal separations between 200 and 5000 km, vertical separations resolved by standard pressure levels between 1000 and 100 mb, and temporal separations from 6 to 24 hours. Some interesting findings have been as follows:

- The joint space-time autocorrelation function of wind indicates a downstream movement of maximum correlation, considerably slower than that predicted by Taylor's 'frozen turbulence' hypothesis.

- For temperature and geopotential autocorrelations, there are systematic variations, both in length scales and in anisotropy, between tropics and mid latitudes, and between levels. These are probably sufficiently large to be taken into account in objective analysis.
- The spatial autocorrelations of zonal and meridional wind components deviate systematically from the forms commonly assumed in objective analysis schemes (see Fig. 21). These deviations appear to be a feature of the general circulation, associated with the poleward transport of angular momentum.

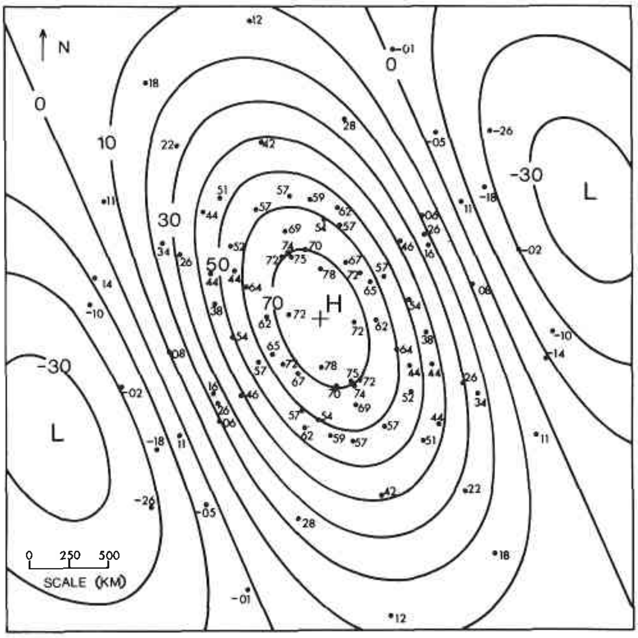


Fig. 21. Contours for the Australian region of the 500 mb winter best fitting meridional correlation coefficient function which allowed the orientation and elongation of the axes to be determined by the data.

D3.4 The El Nino — Southern Oscillation Phenomenon

Numerous studies of the nature of the El Nino — Southern Oscillation (ENSO) phenomenon and its relationship to climate fluctuations, especially in the Australian area have been carried out. ENSO is a large scale fluctuation of the atmospheric and oceanic circulation centred on the Pacific. The existence of the ENSO has been known since the start of the century but reasonably complete descriptions and the first postulated theoretical explanations of the phenomenon have only begun to appear over the past decade.

Associated with ENSO are considerable interannual variations of sea surface temperature (SST) in the Pacific and Indian oceans. These SST's have been examined for particular years during which the annual rainfall was extremely high or extremely low over continental Australia. In extremely dry years the SST in general was found to be low over an extensive area from the equator to around 30°S in both the Indian and Pacific oceans adjacent to Australia, while in the very wet years the continent lay in a warm 'bath' which extended over a similar area and even to mid latitudes (see Fig. 22).

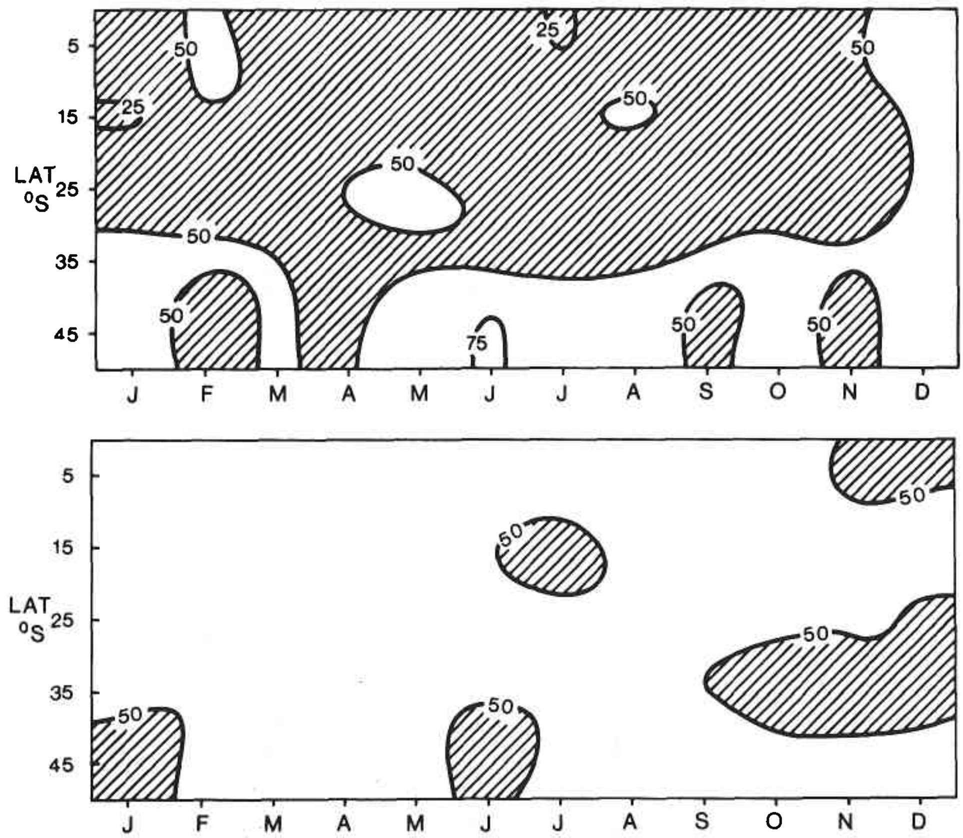


Fig. 22. *Monthly and latitudinal distribution of SST anomaly for the Australian region showing the percentage of available degree square mean monthly SST observations above normal for three dry years (upper) and three wet years (lower); time-space zone values of less than 50 per cent are shaded.*

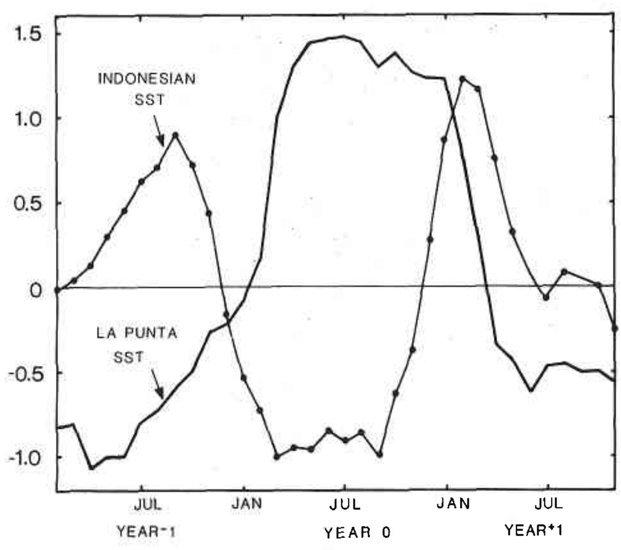


Fig. 23. *SST anomalies (in standard deviations) near Indonesia and at La Punta, South America, composited over four El Nino years (year 0), the years before (year-1) and the years after (year+1) El Nino. SST's are warm on the South American coast and cold near Indonesia during El Nino.*

The pattern of SST was examined for these years at the other 'pole' of the ENSO phenomenon; viz., the eastern tropical Pacific. In general, this area experienced out of phase SST conditions with the Australian region. Studies have also revealed close relationships between seasonal Australian rainfall and atmospheric 'indices' of the Southern Oscillation.

The possible causes of the ENSO have been studied and it was proposed that the phenomenon was the result of a seasonally varying interaction between the ocean and atmosphere over Indonesia. This proposal can account for the quasi-periodicity of ENSO, its phase-lagging to the annual cycle, and the strong relationships between ENSO and SST in the Indonesian area (see Fig. 23). The proposal suggests that changes in Indonesian SST should be the first precursor for ENSO events. Subsequently evidence that this may indeed be so has been found in observational studies.

D4 LONG RANGE PREDICTABILITY

Many varied methods for preparing long range forecasts have been suggested over the years. Using observed data, the validity of the claims for some of these methods was examined. Those based on sunspots or quasi-periodicities of the atmosphere were easily shown to be of no value in long range rainfall prediction for Australia.

Some workers have suggested that polar ice conditions might provide the key to long range prediction. Some of the earliest attempts to assess the extent of the Antarctic pack ice and its variations from year to year using satellite data were made in the early seventies at CMRC. Since 1973 it has been possible to assess broadscale sea ice features using the daily analyses made by the NOAA/US Navy Joint Ice Centre. These data have been used to study the hemispheric variation of the outermost sea ice boundary and to relate it to changing atmospheric conditions. So far, the evidence indicates a major control of the ice extent is by the action of the atmosphere (especially the effect of large depressions) in the short term (hours or days), and more particularly in the longer term (weeks).

The relationship of Australian rainfall to ENSO has been noted above. In the early decades of this century a number of studies suggested that lag relationships existed between the Southern Oscillation and rainfall in Australia and Indonesia, which might make long range prediction of seasonal rainfall feasible. Verification of these suggestions on later independent data has confirmed this, and further work has also indicated that the Southern Oscillation could be used to predict the date of the wet season onset over tropical Australia.

The close relationship between SST and ENSO suggested that SST in this area might be a useful long range predictor of other variables related to ENSO. For instance, based on two separate periods of data, determined by the availability of SST records for the north Australian-Indonesian region, it was found that years with relatively many tropical cyclones were preceded by high north Australian SST, low east Pacific SST and low Darwin pressure (see Fig. 24). Such years also tended to be followed by the reverse pattern. The north Australian-Indonesian SST anomalies show strong persistence from about January through to October with a tendency to dissipate or change sign during November. Changes in the SST anomalies lead changes in the Southern Oscillation and east Pacific SST by about a season, and thus offer a possible means for predicting El Nino, Australian seasonal rainfall, crop yields, and tropical cyclone numbers, as well as Indian summer monsoon rainfall.

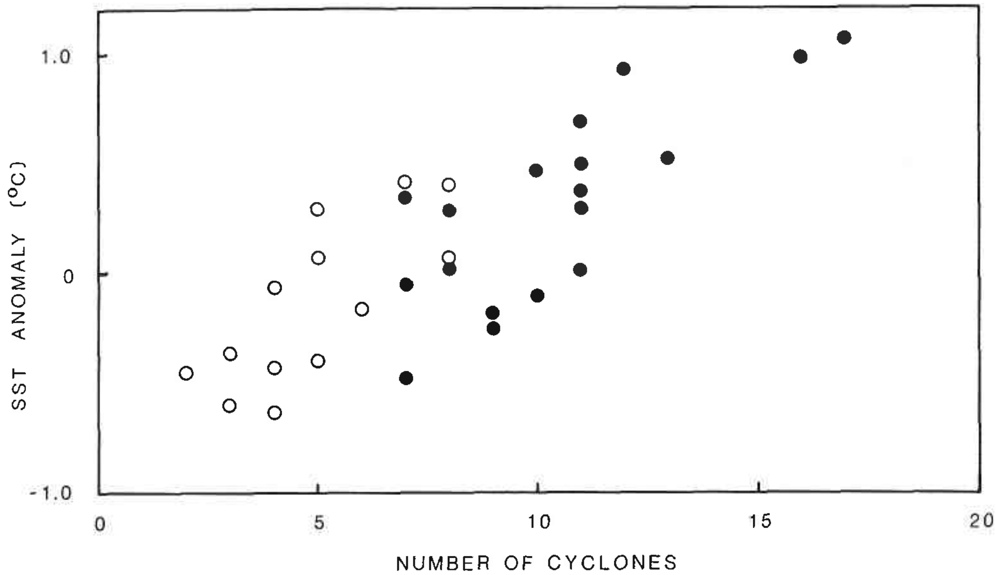


Fig. 24. Scatter diagram of Australian tropical cyclone numbers versus the Indonesian SST anomaly averaged from September to November just prior to the commencement of the cyclone season. Data for 1964 to 1982 is shown by full circles and for 1913 to 1931 by open circles.

References

TALJAARD, J.J. (1968). Climate frontal zones of the southern hemisphere. **NOTOS**, 17: 23–34.

TALJAARD, J.J., H. VAN LOON, J.L. CRUTCHER and R.L. JENNE (1969). **Climate of the Upper Air Part 1. Southern Hemisphere, Volume 1**; US Navy, NAVAIR 50-IC-55.

3. CLIMATE RESEARCH

Overview

The essential theme of the Centre's climate research program has been to develop and use numerical models to increase the understanding of the physical basis of climate. This has included the improvement of the mathematical methods for integrating equations governing the atmosphere's larger scale behaviour as well as the representation of the physical processes relevant to longer term atmospheric evolution.

Thus in the early stages of the Centre's existence most of its research effort concentrated on the development of a number of numerical models suitable for a variety of purposes, and which were to be assessed by model intercomparison studies. As it eventuated, the intercomparisons were not carried out at CMRC/ANMRC in any formal study. Nevertheless, the impetus for model development remained for at least the first half of the Centre's existence. Thereafter the application of these models to particular tasks gave rise to a series of geophysical experiments designed to quantify the role of basic atmospheric processes in maintaining the general circulation, as well as to evaluate anthropogenic influences such as carbon dioxide increases. In particular, a hemispheric grid model was used for a number of these controlled experiments, a two-level spectral model (for economy) for interannual studies, and global semi-spectral or Fourier models for short term climate and middle atmosphere studies. A global spectral model developed for numerical weather prediction was also used for some general circulation studies.

The recognition of the importance of oceanic influences on the behaviour of the atmosphere gave rise to a number of oceanographic studies in the second half of the Centre's life span, including the development of a coupled atmosphere-ocean modelling capability.

C1 GENERAL CIRCULATION MODELLING

C1.1 Geophysical Experiments

Once it is established that a particular model formulation will give a 'reasonable' representation of the atmosphere's large scale behaviour, a control run or long integration may be generated. The effect of specific perturbations to the modelled atmosphere can then be assessed by comparison of the experimental run with the control. In turn this may provide considerable insight into the functioning of the real atmosphere, explaining why certain regimes are preferred to others.

A number of these experiments has been performed in the Centre using a stereographic general circulation model. This model was developed initially at GFDL, Princeton, USA (Manabe *et al.*, 1965; Smagorinsky *et al.*, 1965; Manabe and Hunt, 1968). It extends from the earth's surface to the stratosphere with 18 levels in the vertical and 20 grid points from equator to pole (N20 resolution); it incorporates annual mean radiation forcing, the hydrologic cycle, land-sea contrast, but no orography. After establishing this model's performance in representing the annual mean conditions, an extensive control run was generated forming the basis for assessing subsequent experiments. Some of these are described in the following.

C1.1.1 Volcano Experiment

The injection of volcanic debris into the tropical stratosphere was simulated using the 18-level N20 polar stereographic model. Its basic effect was limited to back-scattering of the incoming radiation during the 150 day integration. Transport of the debris within the model appeared to be well simulated in comparison with observed behaviour of radioactive debris in the atmosphere. Only slight perturbations were produced in the large scale wind distributions, but the surface temperature changes revealed a cooling of 0.3°K on a hemispheric mean basis, and about 0.75°K for the tropical zonal mean (see Fig. 25).

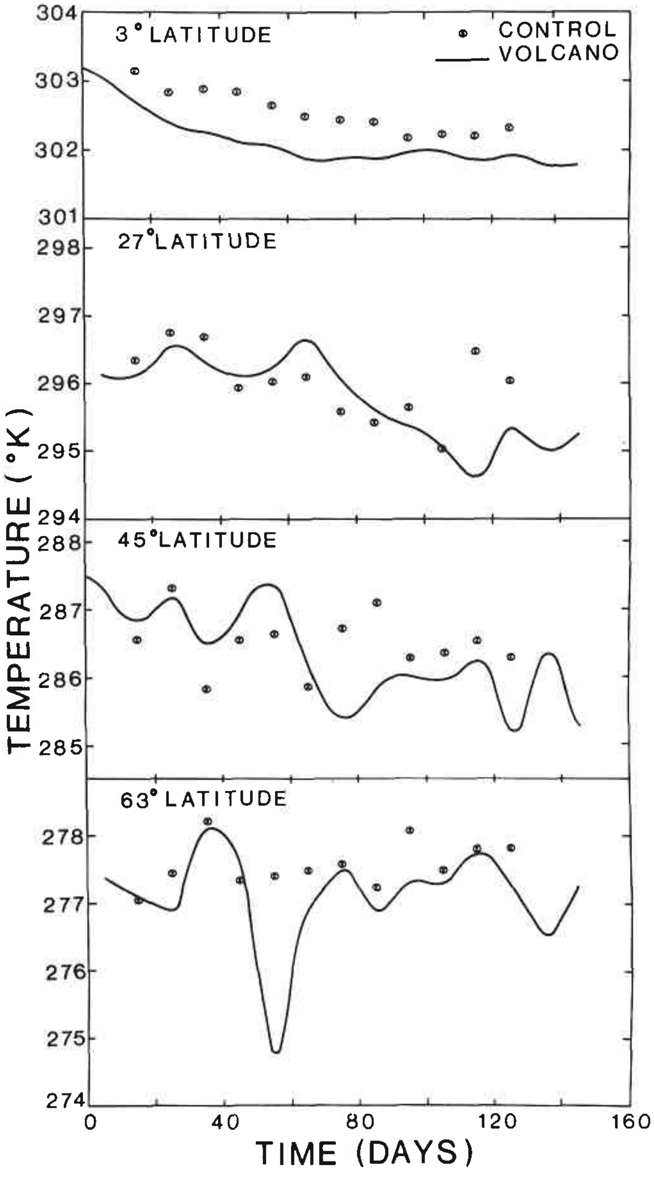


Fig. 25. Temperatures at various latitudes and times for the control and volcano integrations using the N20 hemispheric polar stereographic model.

C1.1.2 The Role of Clouds

A number of experiments was designed to assess the role played by clouds in the radiative balance of the modelled atmosphere, and how realistically they should be specified. In one experiment with the N20 stereographic model the climatologically defined clouds used in the radiation calculation were removed entirely. This resulted in a general warming of the earth's surface and lower atmosphere as expected, but there was relatively little response from the general circulation as a whole. The zonal mean latitude-height distributions of zonal wind and kinetic energy were almost identical with the control run, while synoptic distributions of most model variables revealed little change in character attributable to the removal of cloud.

Further investigation of the possibility of the coupling of radiative perturbations associated with variable cloud cover and dynamical changes in the atmosphere has been made using a two-level general circulation model (see Section C1.4.2). The control model forecast its own cloud cover to generate a time-averaged zonal mean cloud distribution. This distribution then replaced the forecast clouds in the model, and a new set of statistics was produced. Comparison of the two again showed very little difference in the zonal mean properties of the general circulation. An indication of the difference in synoptic characteristics is shown in Figure 26.

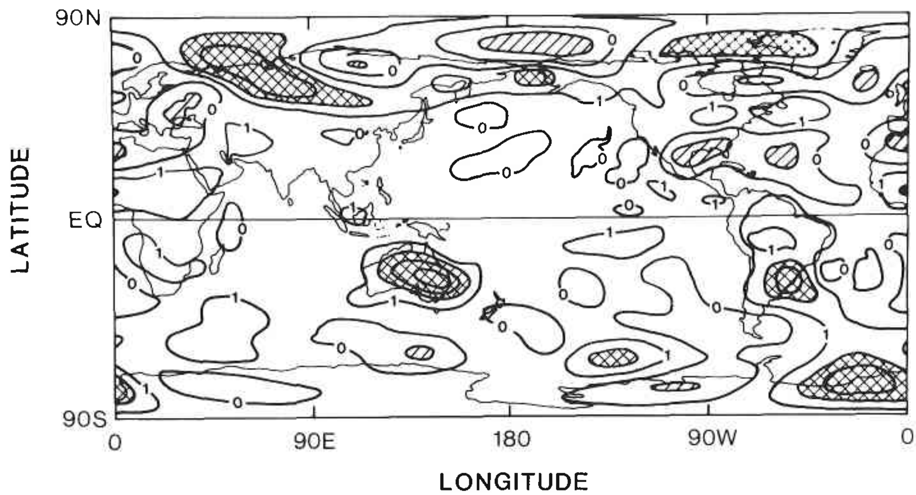


Fig. 26. Temperature difference (K) at 750 mb between the control experiment with self-generated cloud, and a re-run using time and zonally averaged clouds from the control experiment. Both are averaged for integration days 31 to 51 for January conditions. Double hatching indicates the control run was more than 2K warmer than the model with fixed clouds and single hatching 1K colder.

The above results have also been endorsed by an 18-level one dimensional radiative-convective equilibrium model of the atmosphere in a series of experiments involving systematic changes to the properties of clouds. The overall conclusion has been that short term cloud transients could be ignored in these climate experiments.

C1.1.3 Sun Weather Relationship

Initially this experiment consisted of inserting a 'hole' in the climatological ozone distribution in the high latitude mid stratosphere of the N20 stereographic model, similar to that observed after a solar proton event. It was hypothesised that the resultant radiative changes would affect the transmissivity of the stratosphere to upwards propagating energy from the troposphere, which in turn would modify tropospheric synoptic systems, thus establishing a stratospheric-tropospheric link. The experiment did indicate changes in the troposphere, particularly the mid latitude upper troposphere where the mean zonal wind was enhanced by approximately 25 per cent. However, it was not possible to identify a clear mechanistic linkage between stratospheric transmissivity changes and perturbations in high latitude upward propagating long waves.

If the response obtained above was due to a direct radiative effect, moving the ozone hole to 45° where the response was a maximum should enhance it. This was tested and the results obtained are shown in Figure 27 which indicates that the response was not zero for the 45° hole, but markedly reduced in amplitude and different in character, lending support to the original hypothesis.

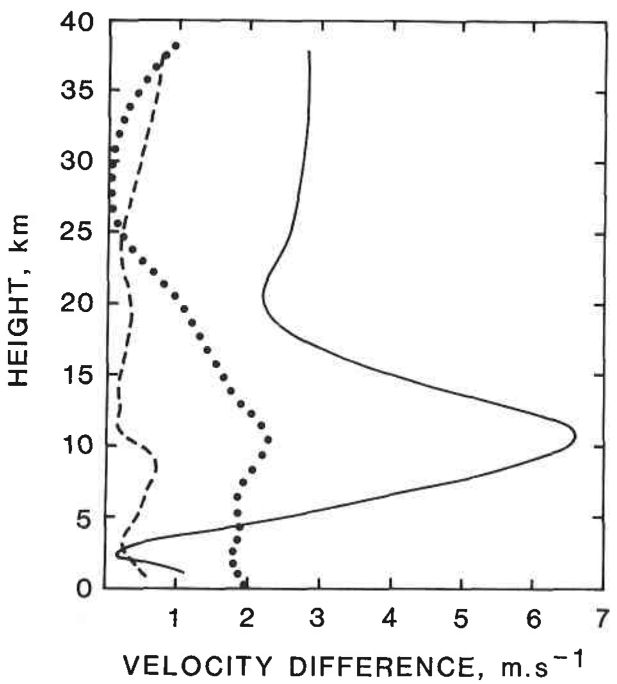


Fig. 27. Absolute values of the mean zonal wind differences for the control run minus the sun weather experiment with the high latitude 'hole' in the ozone distribution (full line), the control run minus the 45° latitude 'hole' (dotted line) and the control run minus noise (dashed line). The noise experiment is included to indicate the likely magnitude of the natural variability of the model.

C1.1.4 Variation of the Earth's Rotation Rate

These experiments were performed in an attempt to understand some of the fundamental features of the circulation patterns of the atmosphere, such as what determines the location, number and intensity of the jet streams. The N20 stereographic model's rotation rate was both increased and decreased by a factor of five, and the consequent simulations analysed. This resulted in the jet stream characteristics and the structure of the mean meridional circulations changing radically (see Fig. 28). The latitudinal extent of the Hadley cell varied inversely with rotation rate, and the subtropical jet core was located at the conjunction of the Hadley and Ferrel cells in both cases. A unique relationship was found between the region of descending air and the surface pressure high for each rate; also the maximum latitudinal shear of the mean zonal wind at the height of the jet core attained the same critical value in each case.

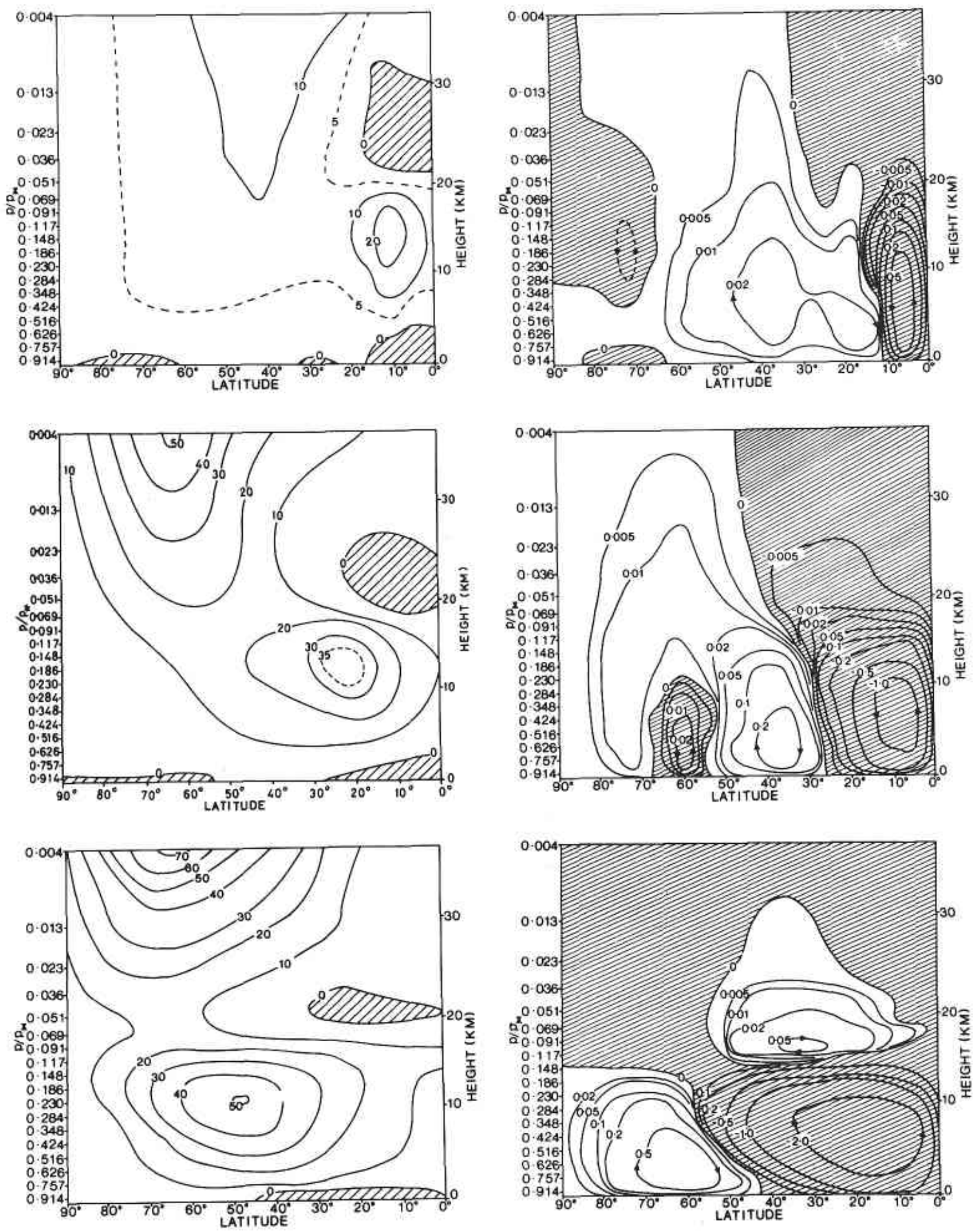


Fig. 28. The left hand side shows the mean zonal wind for 5 times the earth's rotation rate (upper), the standard rotation rate (centre) and 1/5 the rotation rate (lower). The right hand side shows the corresponding mean meridional stream functions.

C1.1.5 Variations in the Earth's Obliquity

Experiments involving variations in the earth's obliquity from its current value of 23.5°, to 0° and to 65° were carried out with the N20 stereographic model. The objective was to evaluate the hypothesis that the occurrence of glacial conditions in the tropics during the late Precambrian ice age were associated directly with this factor.

For the 0° obliquity case, climate was found to be more active than at present, and considerably colder at high latitudes. Thus the model response was the opposite to that claimed by palaeo-botanists to have existed 100 million years ago with subtropical plants flourishing at high latitudes and which was attributed to a much smaller obliquity than the current 23.5°.

The 65° case was more difficult to analyse because of the extreme seasonality involved. While glacial conditions were not obtained over the model tropics, it would appear that for ice age conditions glaciation would occur preferentially at low latitudes as claimed by geologists for late Precambrian conditions 600 million years ago.

C1.1.6 Atmospheric Vacillations

Although not a planned geophysical experiment, analysis of a time series of 124 days of data obtained from the N20 stereographic model revealed a marked oscillation or vacillation in the hemispheric mean of both the eddy available potential energy and the eddy kinetic energy. This vacillation had a period of about 20 days and appeared to be similar to one recently observed in the actual atmosphere during winter.

C1.2 Fourier Modelling

Fourier model development commenced in the early 1970's with the increasing requirement to model the atmosphere on a global basis. One approach was to represent the atmospheric variables by a truncated series of spherical harmonics. This approach, known as the spectral method, was being developed in the Centre for numerical weather prediction. Another solution, the one adopted, was to develop a hybrid model combining the spectral method for east-west variability and grid point representation in the north-south direction: the so-called Fourier model. A zonally symmetric model which generates balanced initial fields for the first term of the Fourier series was also programmed at this time to assist in diagnosing some of the numerical problems in the early development of the Fourier models.

The Fourier model was first tested with a relatively coarse N20 resolution and a zonal Fourier series truncated at wave number 10. Early tests were also made in NWP mode at N30 resolution, truncation at wave number 15, and five levels in the vertical; the latter proved comparable to other ANMRC weather forecasting models. To extend the Centre's modelling capabilities it was decided at this time to concentrate development on two general circulation models, one to investigate upper atmosphere dynamics and the other for short term climate problems.

C1.2.1 The Middle Atmosphere

In the early 1970's considerable interest was emerging concerning the dynamics of the stratosphere and mesosphere. Relatively little was known of this region because of the very limited observations. The need to study the impact of supersonic flight on the stratosphere was also seen to be important. One approach to this problem was via numerical modelling and the development of the global Fourier model was thus extended to a 54-level version reaching 100 km into the atmosphere. As considerable interest was focused on studying the mean circulation patterns of the stratosphere, and coupling between the stratosphere and mesosphere, vertical resolution was increased somewhat to the detriment of horizontal resolution (15 wave numbers and N20); the hydrologic cycle, topography and the daily cycle were omitted. Land-sea contrast was incorporated; a simple radiation approximation was employed above 70 km; and sea surface temperatures were fixed.

The first experiment with this model was the generation of 30 days of simulated atmospheric statistics for January conditions. As this was one of the first three dimensional simulations of the upper atmosphere, considerable interest centred on this basic climatology which gave rise to several unique results. The north-south wind in the middle atmosphere generally has been considered to be a steady flow of the order of 1 to 2 ms^{-1} directed from the summer to the winter pole. However in the model tropical atmosphere this wind was found to have an unusual layered structure which also has been explained recently by theoretical work both at the ANMRC and in the USA, and determined to be an inertial instability due to the excessively strong winter mesospheric jet in the model. Also of interest was the multi-celled structure of atmospheric flow near 50 km. Below 20 km this structure is well observed and also reproduced by the model, but current views based on simpler models are that at higher levels the pattern should be single-celled from the summer to winter pole. Resolution of these differing predictions should enhance our understanding of the region.

The 54-level model was the first to reproduce the so-called two-day wave known to occur in the summer mesosphere (above about 50 km), where it dominates the north-south wind distribution. It has a wave number three pattern, moves westward and at a given location reverses direction each 24 hours (see Fig. 29).

More recently a diurnal version of the model has been run, incorporating dissipation generated by breaking internal gravity waves in the mesosphere. Surface pressure tides very similar in amplitude and phase to those observed are obtained. Some critical features such as the mean meridional circulation and the mesospheric polar night jet are reproduced more realistically, and easterlies are now obtained above this jet in agreement with observation.

C1.2.2 18-Level Fourier Model and Drought Studies

A short term climate model was constructed with a resolution of N30, 18 levels in the vertical and 21 zonal wave numbers. It incorporates the hydrologic cycle, topography, land-sea contrast, fixed sea surface temperatures and a surface hydrology scheme.

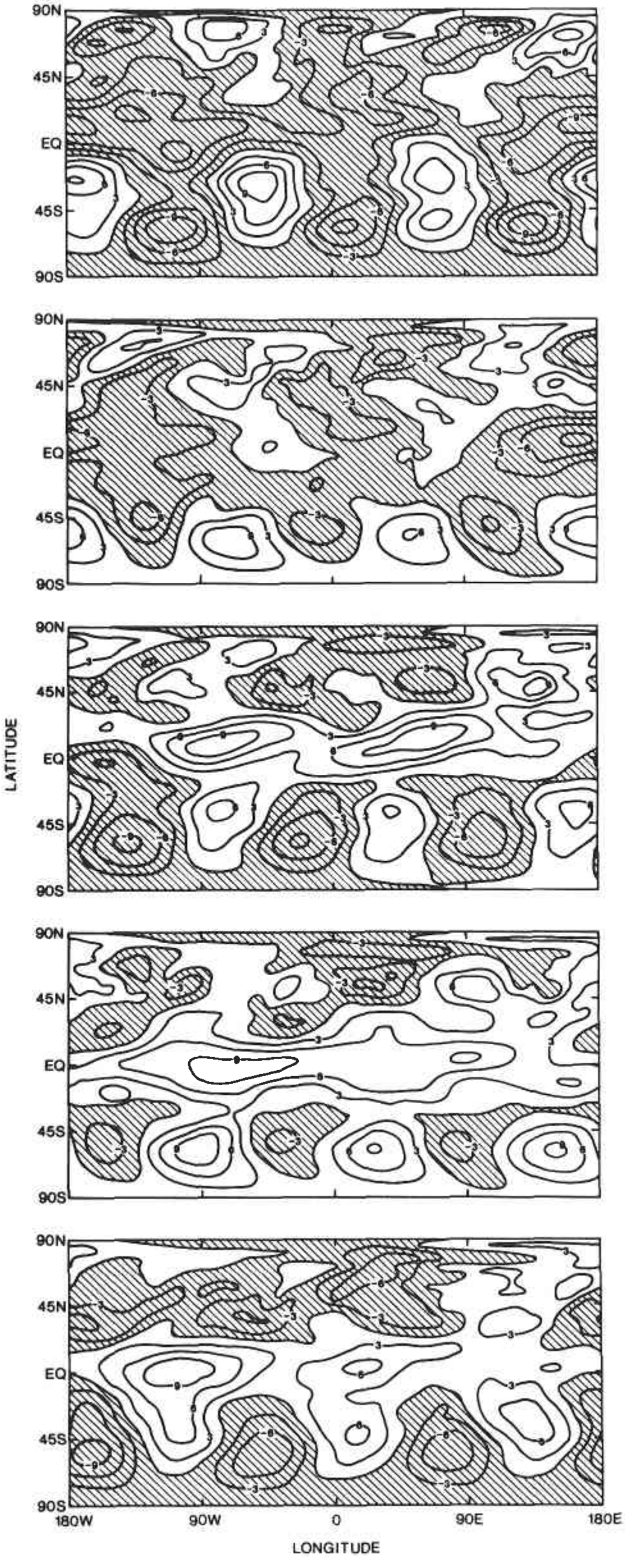


Fig. 29. *Global north-south winds at 90 km at six hourly intervals. Hatched areas are regions with southward winds. The progression of the two-day wave can be seen clearly by following the feature propagating in from the right hand side of the diagram at approximately 45°S. The reversal in direction at a given location is seen by comparing the maps at 0 and 24 h. Wind velocities in ms*$^{-1}$ *are indicated on the contours.*

In 1977 it was decided that this model should be used to investigate a problem of immediate relevance to Australia, that of rainfall variability, particularly drought. Consequently a series of SST anomaly experiments was embarked upon in the late 1970's using the Fourier model, the rationale for these being based on the observational studies of the Diagnostic Studies Group (see Section D3.4).

The first drought experiment involved the insertion of cold SST anomalies north of Australia in the tropical Pacific and Indian oceans, and the second, in addition to these, included a warm anomaly in the eastern tropical Pacific. The analysis of the model response in these two experiments was complex but implied that in the Australian region there was a 'primary' response to the colder SST which induced 'secondary' responses over South America, South Africa and the USA (see Fig. 30). The reduction in northern Australian rainfall could be related directly to the reduced evaporation over the colder oceans releasing less energy into the atmosphere and thus weaker convergence of air masses. In the second experiment a similar rainfall pattern occurred over Australia implying that both SST patterns induce a similar model response. Rainfall also increased on the west coast of South America, which is observed during El Nino years.

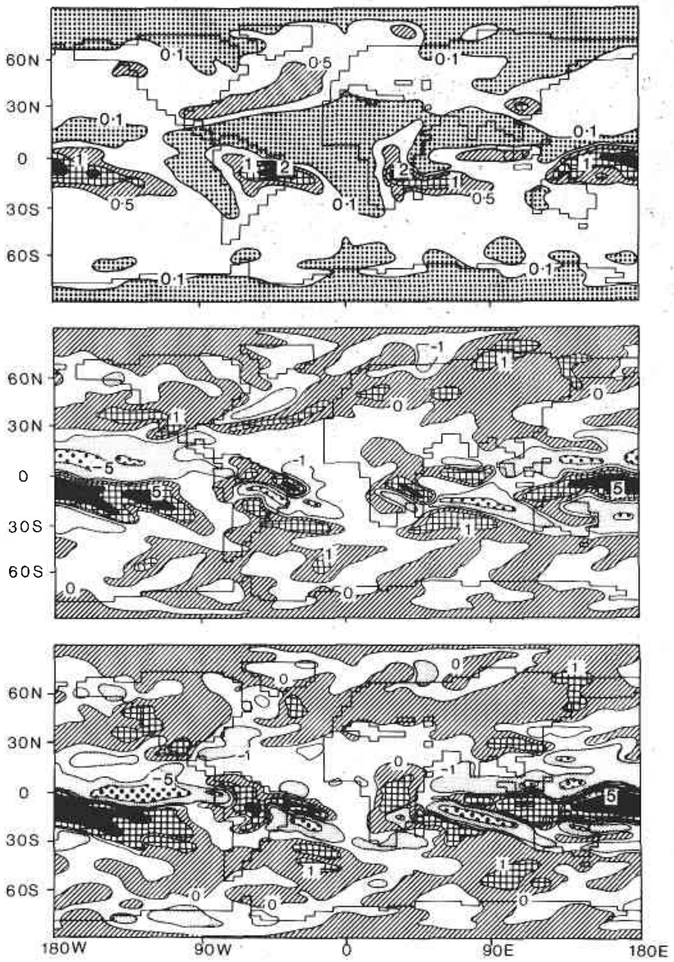


Fig. 30. The precipitation for the control experiment (upper), units cmd⁻¹, the precipitation differences between the control and the first drought experiment (centre), and the precipitation differences between the control and the second drought experiment (lower). Units for these latter two are mmd⁻¹, and the results are averaged over 70 days. Positive departures (i.e., decreased rainfall) are in black, double and single hatching; negative departures are in large dots, small dots and clear.

C1.3 Southern Hemisphere

In the early seventies an N30 version of the stereographic model (Section C1.1) with nine levels in the vertical was also developed specifically to study the southern hemisphere circulation. It was integrated for more than 100 days for fixed March conditions. Synoptic analysis of the model's results showed that a good representation of the atmosphere was obtained: storm tracks were realistic, major subtropical jets were produced over Australia and South America, with a more transient one over South Africa. A comprehensive analysis was made of one particular storm in which the model reproduced a sequence of events typical of the real atmosphere, for example frontal-type development manifested as concentrations of temperature and moisture.

C1.3.1 Sea Surface Temperature Anomalies

One of the early geophysical experiments made in 1972–73 using the nine-level N30 polar stereographic model was to attempt to determine the effects of various SST anomalies on the behaviour of the large scale atmospheric flow. A mid latitude warm SST anomaly centred near New Zealand resulted in the development of a blocking anticyclone at approximately day 24 of the integration, and lasted for some ten days. When the anomaly was introduced ten days later the initial reactions were similar to the first situation but the longer term response differed — the blocking sequence was not evident and the flow in the middle latitudes was more zonal.

When a warm tropical anomaly was superimposed on the March SST, significant departures from the control were obtained. Cyclone development in the anomaly area was sustained and their movement south and downstream reinforced high latitude systems.

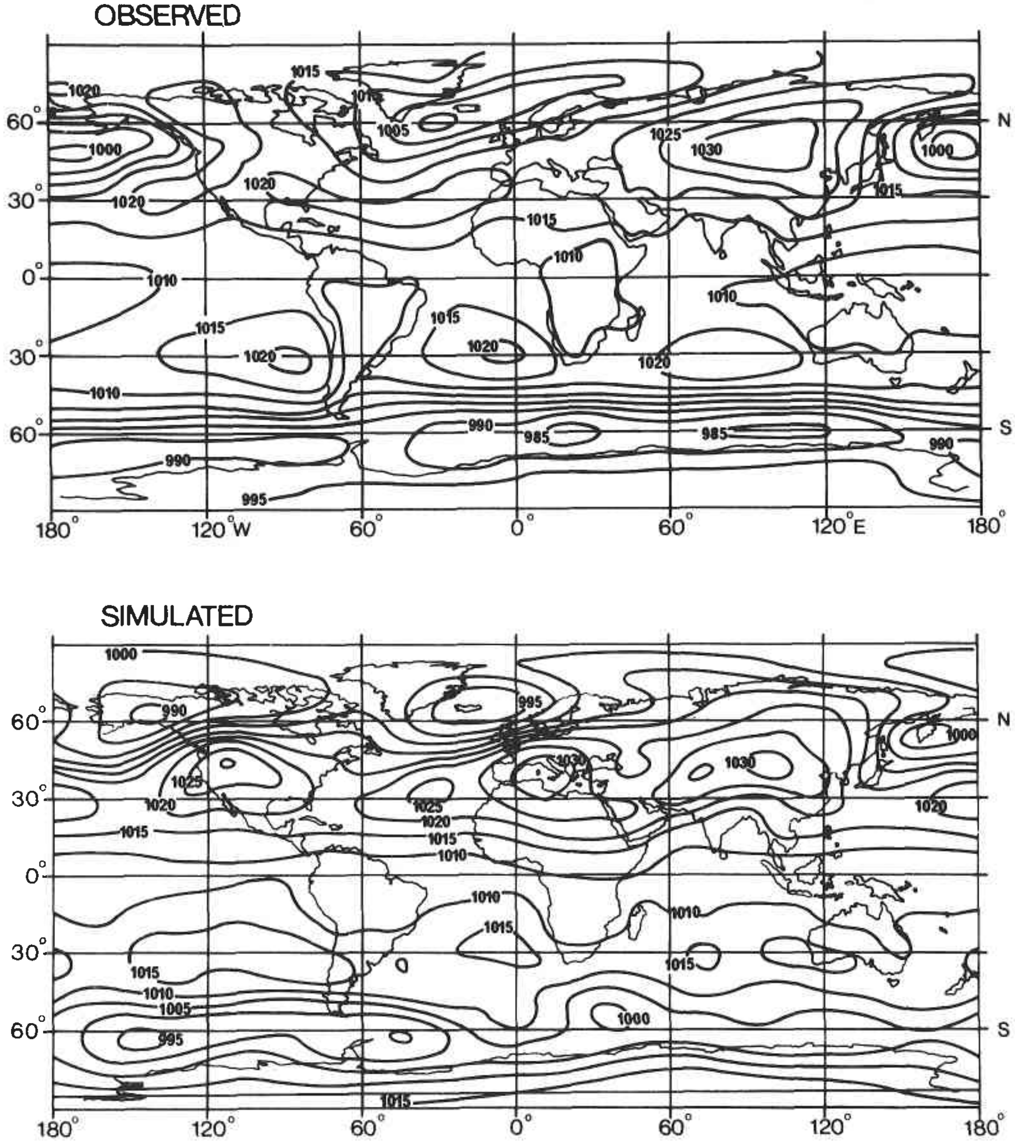
C1.4 Spectral Modelling

C1.4.1 Nine-Level Global Simulation

In parallel with the development of the spectral model for operational numerical weather prediction (Section W2.1.2) it was decided in 1974 to assess its performance in a general circulation simulation. At this early stage no one had attempted to run a spectral model with the extra physical parameterizations required for such a simulation and utilizing semi-implicit time differencing.

Physical parameterizations developed by GFDL in the USA (Smagorinsky *et al.*, 1965) were incorporated in a wave number 15 rhomboidal truncation, nine-level global spectral model which was run for perpetual January conditions. The study demonstrated the usefulness of the spectral model in conducting large scale simulations of the general circulation of the atmosphere. The accuracy afforded by the spectral algebra, the efficiency provided by semi-implicit time integration, and the capability to incorporate comprehensive physical parameterizations successfully in a spectral model were clearly indicated. The simulation of the mean sea level pressure and precipitation for January are shown in Figure 31.

The success of this model also when implemented on the NCAR (USA) CRAY1 computer, led the NCAR Climate Group to adopt it (with a new radiative transfer code) as the Community Climate Model (Version Ø) which has now been made available to the university research community within the USA.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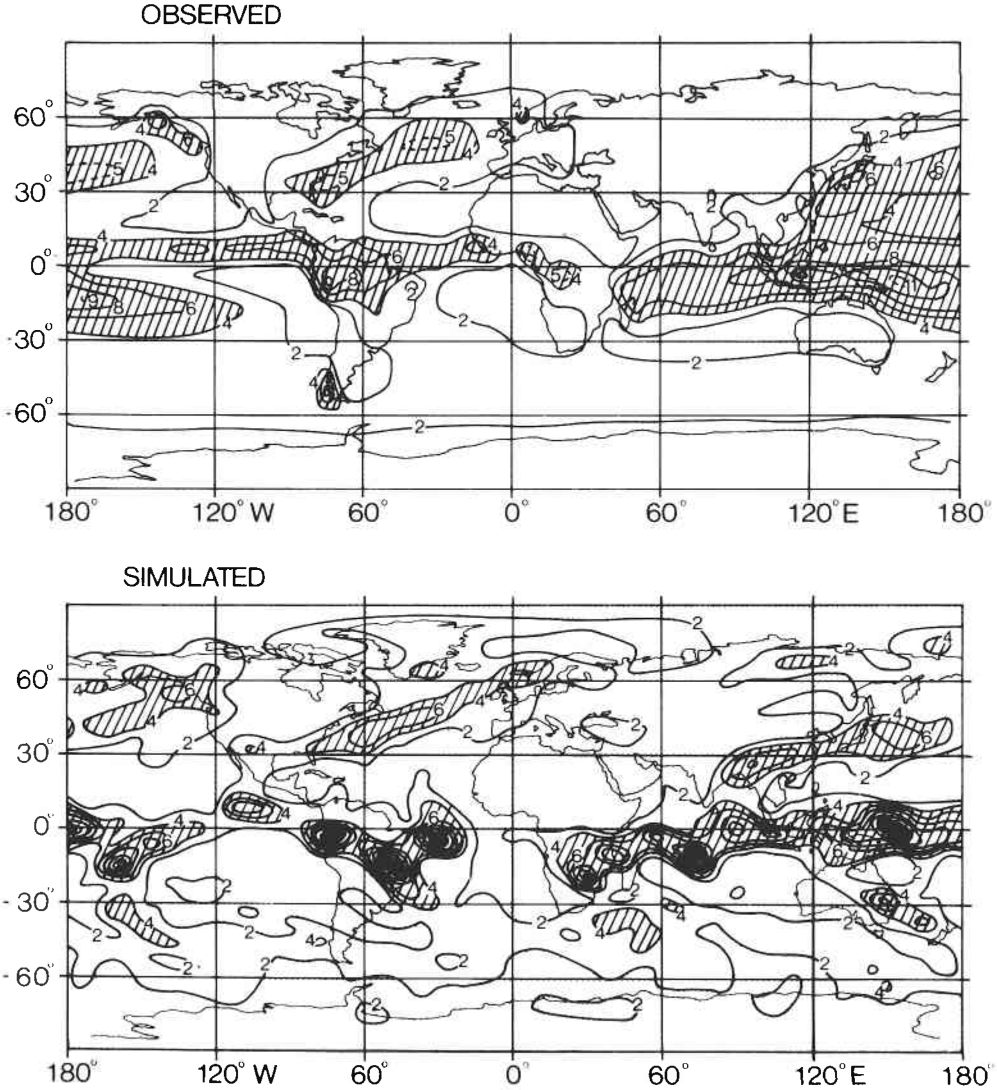


Fig. 31. *(a) Mean sea level pressures (mb) contours at intervals of 5 mb. The observed data are from the tabulation of Schutz and Gates (1971) and the simulated data by the general circulation version of the ANMRC spectral model averaged at 6 h intervals for a 30 day period.*
(b) Precipitation rate (mmd^{-1}) at contour intervals of 2 mmd^{-1}. Black areas represent values in excess of 14 mmd^{-1}, cross hatching 4 to 14 mmd^{-1}, clear 2 to 4 mmd^{-1}, and stippling less than 2 mmd^{-1}. The observed data are for the December-February period from Schutz and Gates (1972).

C1.4.2 Two-Level Model

Multi-annual integrations of atmospheric models can provide insight into processes associated with climatic variability. However, if only limited computer resources are available, then such studies are not feasible with, for example, the multi-level model outlined in Section C1.4.1. Thus, a similar model has been developed in the ANMRC but with a minimum vertical resolution (two levels) in which the gross features of atmospheric flow could be represented. Maximum timesteps with the spectral method were achieved by semi-implicit time integration, and the horizontal resolution was set initially at rhomboidal wave number 15. This was increased later to wave number 21.

The equations were cast in the flux form rather than the usual advective form, the former having the advantages of vertical derivatives in a two-level model being better represented, and superior conservation properties. The physical parameterizations were based on those used in the RAND two-level model (Gates and Schlesinger, 1977) which allowed for ground hydrology, radiation, convection and self-generated cloud cover. Subsequent modifications gave improved surface fluxes and cloud cover.

Two experiments have been conducted in which the model was integrated for both perpetual January and July conditions, each for 150 days. Some of the cloud related aspects are referred to in Section C1.1.2. A higher horizontal resolution model (wave number 21) was developed in which ground hydrology was enhanced to include snow cover; a sea ice model was also included so that the system could

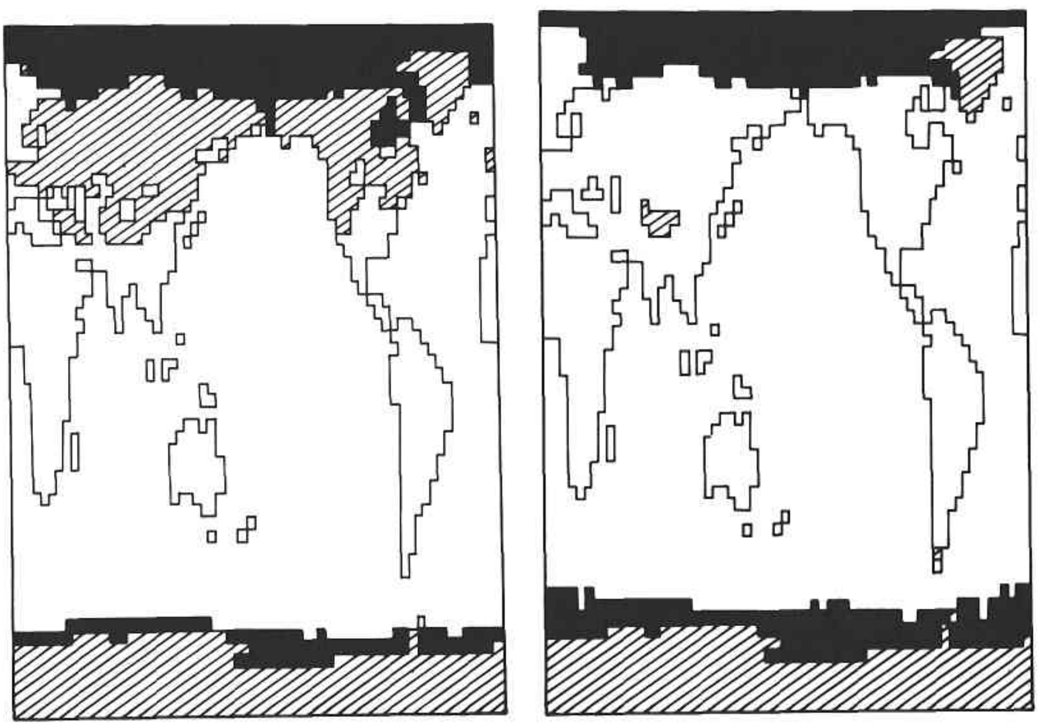


Fig. 32. Snow cover (hatched) and sea ice cover (black) for 31 January (left hand side) and for 31 July (right hand side) for year five of the 10 year two-level spectral model integration.

predict ice growth and decay according to season. Sea surface temperatures were upgraded and available to the model on a monthly basis (see Section C1.5.2). The atmosphere-ice model was then integrated for ten years, the results of which are currently being analysed. The snow and ice cover exhibit realistic interannual variability (see Fig. 32), as do the other model variables, and it is this aspect that is being assessed in terms of the feasibility of applying such models to the study of drought and other long term features of the real world's climate.

C1.5 Coupled Atmosphere-Ocean Modelling

The longer term behaviour of the atmosphere is known to be closely linked with the sea surface temperature and thus to simulate it correctly coupled atmosphere-ocean models are necessary. Several approaches to this problem have been made within the Centre.

C1.5.1. Nine-Level Spectral Model

A one dimensional mixed layer model of the upper 200 metres of the ocean was developed to predict mixed layer depth and sea surface temperature. This model was coupled with the ANMRC southern hemisphere spectral general circulation model (Section C1.4.1). As there was no horizontal coupling in the ocean model, it was attached effectively to individual grid points of the atmospheric model. The results obtained for perpetual January conditions suggested that sea surface temperature anomalies are induced primarily by atmospheric forcing rather than by mechanisms internal to the oceans. A more detailed analysis of the experiment indicated that positive feedback between the ocean and atmosphere was likely to be an important process in producing seasonal variability.

A further experiment with this coupled configuration was to insert a large tropical SST anomaly, which was free to evolve in space and time, in the central South Pacific, similar to one observed during the winter of 1977 which persisted into the summer. Comparison was made with the atmosphere-only nine-level spectral model with a fixed anomaly in the climatological SST in the same location. In both cases precipitation increased over the western half of the anomaly but decreased over Indonesia and the tropical regions of southern Africa and South America (see Fig. 33). In the coupled model the anomaly persisted with a substantial area remaining after 80 days. However, it did move westward due to enhanced mixing and upwelling at its eastern edge, and a decrease in these components on its western edge. Although substantial similarities were observed in both atmospheric responses, the coupled model indicated the desirability of performing anomaly experiments with coupled oceans.

C1.5.2 Two-Level Spectral Model

With the above indication of the likely role of feedback processes between the ocean and atmosphere in seasonal variability simulations, preliminary work was commenced in late 1979 to couple the two-level spectral model (Section C1.4.2) with a simple 1½ layer advective ocean model. An experiment was conducted in which the (uncoupled) ocean model was 'driven' by data from January and July control runs of the atmospheric model, for a twelve year integration. Although some anomalies were generated in SST by the use of the non-interactive atmospheric

Fig. 33. *80 day average precipitation differences (mmd^{-1}) resulting from a tropical SST anomaly (°C) (upper) when applied as an initial condition for the coupled ocean-atmosphere model (centre), and as a fixed bottom boundary condition for the atmosphere-only nine-level spectral model (lower).*

forcing, the mixed layer depths were quite reasonable and currents in the large scale flow patterns were in the correct locations.

Further investigation of an appropriate ocean model for climate research confirmed the suitability of an advective mixed layer model with imposed surface heating and wind stress, and vertical entrainment of cold water from the deep layer into the mixed layer. An ocean model incorporating these features has been coupled with the two-level climate model and the combined system is undergoing testing and refinement prior to a seasonal cycle experiment.

C2 OCEANOGRAPHIC STUDIES

C2.1 South East Asian Seas

The oceanic behaviour south of Celebes, where the Makasar Strait meets the Flores Sea, has been studied. This region is of particular interest because of its upwelling, thus supporting a significant Indonesian fishing industry, and it has a reasonable record length of sea surface temperature data which have been used in studies of the interaction of the oceans and the circulation of the atmosphere (see Section D3.4). Non-linear equations with discontinuous solutions have been shown to describe the ocean flow in this area; this has led to the development of an analytical method for handling deep baroclinic flows of an arbitrary Rossby number. (This technique was also applied to the problem of flow around an island. It showed an asymmetry in the flow caused by vortex stretching; a result which had only been hinted at by previous workers.)

A second related investigation concerned the shallow flow across the equator in the South China Sea (within the Makasar Strait), despite the large variation in the Coriolis parameter between the two basins. Bottom water pressure variation between basins was identified as one of the primary mechanisms underlying this flow. The study also showed that provided the wind stress is in the correct direction, there is a balance between frictionally controlled redistribution of vorticity, vortex stretching creating vorticity and beta-effects destroying it such that the flow is symmetric within the Strait. This frictional control has since been supported by limited observations made in the area. These imply that kinematic waves may propagate along the Strait and be important to the dynamics of the region.

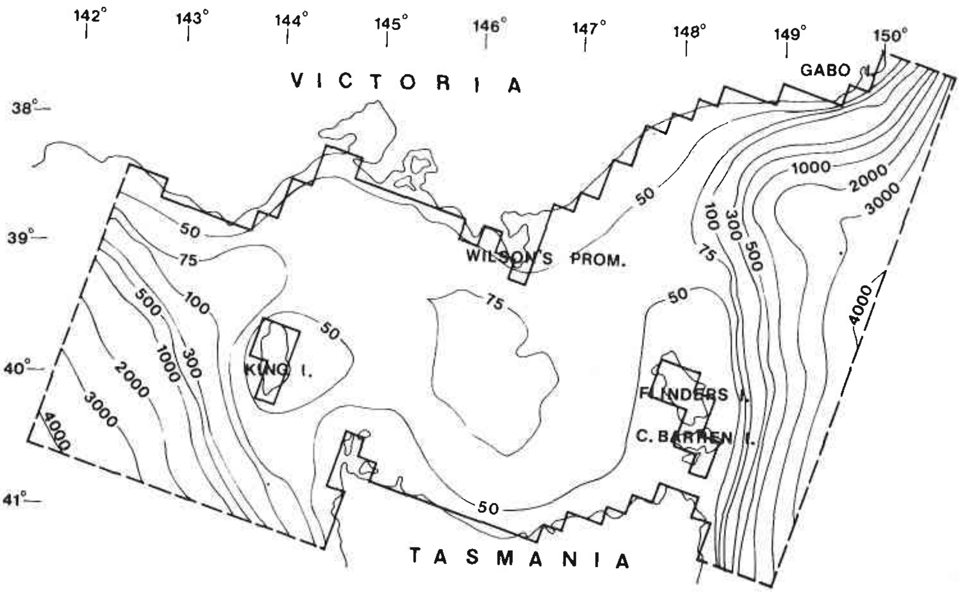
Bottom friction is also known to be important in the Java Sea. Previous attempts to model this region with a depth integrated model have failed to capture a potentially important western boundary current off the coast of Sumatra near Singapore. The influence of a bottom stress induced secondary circulation has been found to be a key aspect; this mechanism appears to be important only in shallow equatorial seas. In the limited observations available this current shows up weakly, and it may be of importance for eastward shipping routes from Singapore.

C2.2 Great Barrier Reef

The lagoon of the Great Barrier Reef was the subject of a collaborative study with AIMS (Australian Institute of Marine Science). What appear to be the largest pure kinematic oceanographic waves were identified in this area and modelled numerically. Unlike those kinematic waves hypothesised for the Makasar Strait, these are controlled by bottom friction rather than lateral friction.

C2.3 Bass Strait

A two dimensional model of the hydrodynamics of Bass Strait was developed for the Victorian Institute of Marine Sciences (VIMS). The governing equations were linearised and vertically integrated on a grid with solid or open boundaries as required by the geography of Bass Strait. The two forcing mechanisms considered were surface winds, and tidal oscillations at the boundaries. An analytical model of



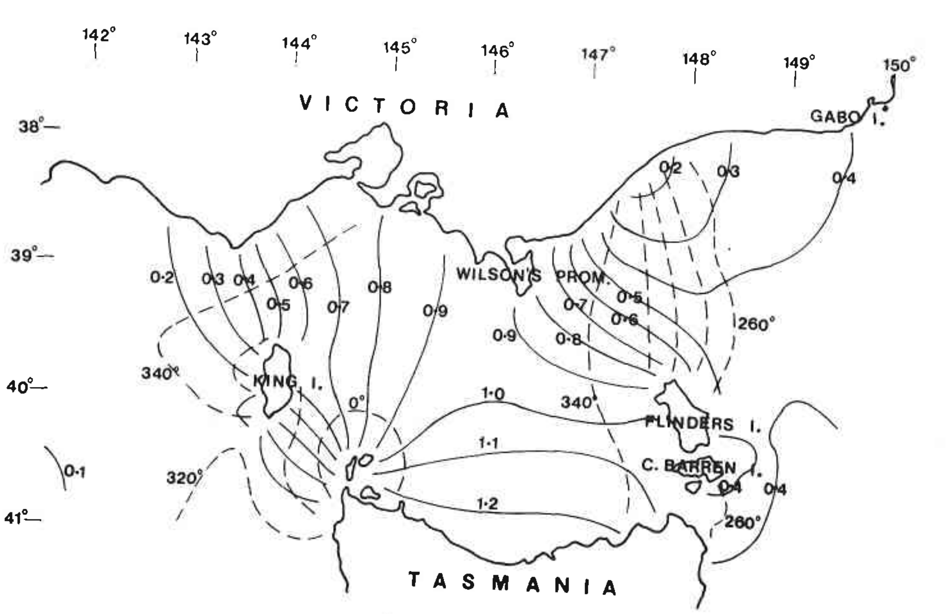


Fig.34. *Bass Strait numerical model geometry depicting the bathymetry and model boundaries (upper). Contours of amplitude (solid lines, metres) and co-phase (broken lines, degrees relative to EST) of the* M_2 *tidal constituent.*

flow in a rectangular basin with open ends was also constructed to verify some of the numerical results and the sensitivity of the open boundary conditions. For instance, the effect of a step change in depth (as used for the continental slope) was predicted by the numerical model to cause a closed gyre over the step, and this was validated by the analytical model.

The vertically integrated model was subsequently extended to three dimensions. Circulation patterns corresponding to either surface wind or tidal forcing can be generated at any depth and significant upwelling and downwelling motions along the Victorian and Tasmanian coastlines can be predicted. The bathymetry and geometry of the numerical model, and an example of the tidal output are shown in Figure 34.

This development work was assisted by a number of instrument deployments in Bass Strait designed and carried out in collaboration with VIMS. Accurate tidal measurements were taken which were used as input data along the open boundaries of the numerical model. The model is now used by various consulting and marine organizations to obtain tidal and current information on Bass Strait.

References

GATES, W.L. and M.E. SCHLESINGER (1977). Numerical simulation of the January and July global climate with a two-level atmospheric model. **J. Atmos. Sci.**, 34: 36–76.

MANABE, S. and B.G. HUNT (1968). Experiments with a stratospheric general circulation model. I. Radiative and dynamic aspects. **Mon. Wea. Rev.**, 96: 477–539.

MANABE, S., J. SMAGORINSKY and R.F. STRICKLER (1965). Simulated climatology of a general circulation model with a hydrologic cycle. **Mon. Wea. Rev.**, 93: 769-798.

SCHUTZ, C. and W.L. GATES (1971). Global climatic data for surface 800 mb, 400 mb: January. Advanced Research Projects Agency, Rep. R–915–ARPA, Rand Corporation, Santa Monica, 173 pp.

SCHUTZ, C. and W.L. GATES (1972). Supplemental global climatic data: January. Advanced Research Projects Agency, Rep. R–915/1–ARPA, Rand Corporation, Santa Monica, 41 pp.

SMAGORINSKY, J., S. MANABE and J.L. HOLLOWAY (1965). Numerical results from a nine-level general circulation model of the atmosphere. **Mon. Wea. Rev.**, 93: 727–768.

Appendix I

Publications

Papers appearing in international and national journals, or as contributions to monographs. Affiliations of non-CMRC/ANMRC authors are given at the end of this Appendix.

ACKERMAN, T.P. (1977). A model of the effect of aerosols on urban climates with particular application to the Los Angeles basin. **J. Atmos. Sci.**, 34: 531–547.

ACKERMAN, T.P. (1979). On the effect of CO_2 on atmospheric heating rates. **Tellus**, 31: 115–123.

ANDERSON, D.L.T. and **P.F. NOAR** (1974). The synoptic verisimilitude of a mid-latitude cyclone generated in a southern hemisphere general circulation model. **Mon. Wea. Rev.**, 102: 613–629.

BAINES[2], P.G. and **C.B. FANDRY** (1983). Annual cycle of the density field in Bass Strait. **Aust. J. Mar. Freshw. Res.**, 34: 143–153.

BAINES[2], P.G., R.J. EDWARDS[3] and **C.B. FANDRY** (1983). Observations of a new current along the western continental slope of Bass Strait. **Aust. J. Mar. Freshw. Res.**, 34: 155–158.

BARKER, A.A. and **W.R. KININMONTH** (1973). A cloud model to parameterise convection. **J. Appl. Meteorol.**, 12: 1319–1329.

BARTON[2], I.J. and **J.F. LE MARSHALL** (1979). Differential absorption lidar measurements in the oxygen A band using a ruby lidar and stimulated by Raman scattering. **Optics Letters**, 4: 78–80.

BENNETT[4], A.F. and **L.M. LESLIE** (1979). Statistical correction of dynamical prognoses in the Australian region. **Mon. Wea. Rev.**, 107: 1254–1262.

BENNETT[4], A.F. and **L.M. LESLIE** (1981). Statistical correction of the Australian region primitive equation model. **Mon. Wea. Rev.**, 109: 453–462.

BENNETT[4], A.F. and **L.M. LESLIE** (1982). Statistical correction of thickness height prognoses. **Aust. Met. Mag.**, 30: 201–209.

BENNETT[4], A.F. and **L.M. LESLIE** (1983). Statistical correction of dynamical prognoses: The decision problem. **Mon. Wea. Rev.**, 111: 343–352.

BODE[5], L., **L.M. LESLIE** and R.K. SMITH[4] (1975). A numerical study of boundary effects on concentrated vortices with application to tornadoes and waterspouts. **Quart. J. Roy. Meteor. Soc.**, 101: 257–268.

BOURKE, W. (1972). An efficient, one-level, primitive equation spectral model. **Mon. Wea. Rev.**, 100: 683–689.

BOURKE, W. (1974). A multi-level spectral model. I. Formulation and hemispheric integrations. **Mon. Wea. Rev.**, 102: 687–701.

BOURKE, W. (1974). Global 5-level spectral model. **GARP Publication Series** No. 14, Modelling for the First GARP Global Experiment: 206–217.

BOURKE, W. and **J.L. McGREGOR** (1983). A non-linear vertical mode initialization scheme for a limited area prediction model. **Mon. Wea. Rev.**, 111: 2285–2297.

BOURKE, W., B. McAVANEY, K. PURI and **R. THURLING** (1977). Global modelling of atmospheric flow by spectral methods. In: **Methods in Computational Physics**, 17, General Circulation Models of the Atmosphere (J. Chang, ed.), Academic Press, 267–324.

BOURKE, W., K. PURI and **R. SEAMAN** (1982). Numerical weather prediction studies from the FGGE southern hemisphere data base. **Mon. Wea. Rev.**, 110: 1787–1800.

BOURKE, W., R. SEAMAN and **K. PURI** (1984). Data assimilation. In: **Advances in Geophysics**, 23, Issues in Atmospheric and Ocean Modelling Academic Press, (in press).

BOURKE, W., K. PURI, R. SEAMAN, B. McAVANEY and J. LE MARSHALL[6] (1982). ANMRC data assimilation for the southern hemisphere. **Mon. Wea. Rev.**, 110: 1749–1771.

BUELL[7], C.E. and **R.S. SEAMAN** (1983). The 'scissors' effect: anisotropic and ageostrophic influences on wind correlation coefficients. **Aust. Met. Mag.**, 31: 77–83.

BYRNE[8], G.F., **N.A. STRETEN** and J.D. KALMA[8] (1984). The relation between HCMM satellite data and temperatures from standard meteorological sites in complex terrain. **Rem. Sens. Envir.**, 5: 65–77.

CLARKE, R.H. and G.D. HESS[2] (1975). On the relationship between surface wind and pressure gradient, especially in the lower latitudes. **Bound.-Layer Meteor.** 9: 325-339.

DALEY[9], R. and **K. PURI** (1980). Four-dimensional data assimilation and the slow manifold. **Mon. Wea. Rev.**, 108: 85-99.

DAVIDSON, N.E. (1982). Diagnostic capabilities of objective analysis schemes: areal mean vertical motion fields of some weather regimes over Australia. **Aust. Met. Mag.**, 30: 211–221.

DAVIDSON, N.E. (1984). Short term fluctuations in the Australian monsoon during Winter MONEX. **Mon. Wea. Rev.**, (in press).

DAVIDSON, N.E. and **B.J. McAVANEY** (1981). The ANMRC tropical analysis scheme. **Aust. Met. Mag.**, 29: 155–168.

DAVIDSON, N.E., J.L. McBRIDE and **B.J. McAVANEY** (1983). The onset of the Australian monsoon during Winter MONEX: Synoptic aspects. **Mon. Wea. Rev.**, 111: 496-516.

DAVIDSON, N.E., J.L. McBRIDE and **B.J. McAVANEY** (1984). Divergent circulations during the 1978–79 Australian monsoon. **Mon. Wea. Rev.**, (in press).

DOWNEY, W.K. (1974). Meteorological satellites the key to global weather prediction. **Aust. Physicist**, 11: 37–52.

DOWNEY, W.K. (1977). A note on an interesting case of convection. **Aust. Met. Mag.**, 25: 135–140.

DOWNEY, W.K. and D.R. JOHNSON[10] (1978). The mass, absolute angular momentum and kinetic energy budget of model-generated extratropical cyclones and anticyclones. **Mon. Wea. Rev.**, 106: 469–481.

DOWNEY, W.K. and **J.L. McGREGOR** (1978). Some diagnostic aspects of a model retained baroclinic zone. **Aust. Met. Mag.**, 26: 95–105.

DOWNEY, W.K., T. TSUCHIYA[11] and T. SCHREINER[10] (1981). Some aspects of a northwestern Australian cloudband. **Aust. Met. Mag.**, 29: 99–113.

DOWNEY, W.K., R. DEL BEATO[6], R.P. CANTERFORD[6] and P.J. MEIGHEN[6] (1979). A case study of the application of GMS imagery over extratropical Australia. **Aust. Met. Mag.**, 27: 71–129.

DOWNEY, W.K., J.R. YOUNG and **W.R. KELLAS** (1973). A case study of the application of the quasi-geostrophic omega equation near baroclinic zones and implications for filtered baroclinic models. **Aust. Met. Mag.**, 21: 119–154.

FANDRY, C.B. (1981). Development of a numerical model of tidal and wind-driven circulation of Bass Strait. **Aust. J. Mar. Freshw. Res.**, 32: 9–29.

FANDRY, C.B. (1982). A numerical model of the wind-driven transient motion in Bass Strait. **J. Geophys. Res.**, 87: 499–517.

FANDRY, C.B. (1983). Model for the three-dimensional structure of the wind-driven and tidal circulation in Bass Strait. **Aust. J. Mar. Freshw. Res.**, 34: 121–141.

FANDRY, C.B. (1984). Effects of longshore variations in depth on the wind-driven flow in a channel. **Tellus**, (in press).

FANDRY[4], C.B. and **L.M. LESLIE** (1972). A note on the effect of latitudinally varying bottom topography on the wind-driven ocean circulation. **Tellus**, 24: 164–167.

FANDRY, C.B. and **L.M. LESLIE** (1984). A two-layer quasi-geostrophic model of summer trough formation in the Australian sub-tropical easterlies. **J. Atmos. Sci.**, 41: 807–818.

FANDRY, C.B. and **L.M. LESLIE** (1984). The effects of shear stratification on stationary Rossby waves. **J. Geophys. Astrophys. Fluid Dyn.**, (in press).

FANDRY, C.B., R.L. HUGHES and **L.M. LESLIE** (1983). Stationary waves forced by topography in a vertically sheared, stratified, rotating fluid. **J. Aust. Math. Soc.**, B25: 127–144.

FANDRY, C.B., L.M. LESLIE and R.K. STEEDMAN[14] (1984). Kelvin-type coastal surges generated by tropical cyclones. **J. Phys. Oceanogr.**, 14: 582–593.

FORGAN, B.W. (1983). Errors resulting from the use of measured albedos to calculate diffuse irradiance. **Solar Energy**, 31: 105–112.

FORGAN, B.W. (1984). The specification of calibration coefficients and constants for pyranometers: A review. **Solar Energy**, (in press).

GAUNTLETT, D.J. and **D.R. HINCKSMAN** (1971). A six-level primitive equation model suitable for extended operational prediction in the southern hemisphere. **J. Appl. Meteor.**, 10: 613–625.

GAUNTLETT, D.J. and **L.M. LESLIE** (1975). Numerical methods for predicting precipitation in catchment hydrology. In: **Prediction in Catchment Hydrology** (T.G. Chapman and F.X. Dunin, eds.), Australian Academy of Science, 33–46.

GAUNTLETT, D.J. and **L.M. LESLIE** (1982). Current status and future prospects for numerical weather prediction — an Australian perspective. **Aust. Met. Mag.**, 30: 57–68.

GAUNTLETT, D.J. and **R.S. SEAMAN** (1974). Four-dimensional data assimilation experiments in the southern hemisphere. **J. Appl. Meteor.**, 13: 845–853.

GAUNTLETT, D.J., L.M. LESLIE and **D.R. HINCKSMAN** (1976). A semi-implicit forecast model using the flux form of the primitive equations. **Quart. J. Roy. Meteor. Soc.**, 102: 203–217.

GAUNTLETT, D.J., L.M. LESLIE and **L.W. LOGAN** (1984). Numerical experiments in meso-scale prediction over south east Australia. **Mon. Wea. Rev.**, 112: 1170–1182.

GAUNTLETT, D.J., L.M. LESLIE, J.L. McGREGOR and **D.R. HINCKSMAN** (1978). A limited area nested numerical weather prediction model: Formulation and preliminary results. **Quart. J. Roy. Meteor. Soc.**, 104: 103–117.

GAUNTLETT, D.J., R.S. SEAMAN, W.R. KININMONTH and J.C. LANGFORD[6] (1972). An operational evaluation of a numerical analysis-prognosis system for the southern hemisphere. **Aust. Met. Mag.**, 20: 61–82.

GORDON, H.B. (1981). A flux formulation of the spectral atmospheric equations suitable for use in long-term climate modelling. **Mon. Wea. Rev.**, 109: 56–64.

GORDON, H.B. (1984). Synoptic cloud variations in a low resolution spectral atmospheric model. **J. Geophys. Res.**, (in press).

GORDON, H.B. and **R.L. HUGHES** (1981). A study of rotating baroclinic nonlinear flow around an island. **J. Phys. Oceanogr.**, 11: 1011–1014.

HUGHES, R.L. (1979). On the dynamics of the equatorial undercurrent. **Tellus**, 31: 447–455.

HUGHES, R.L. (1980). On the equatorial mixed layer. **Deep Sea Res.**, 27A: 1067–1078.

HUGHES, R.L. (1980). The dynamical response of the ocean to a CO_2 enriched atmosphere. In: **Carbon Dioxide and Climate: Australian Research** (G.I. Pearman, ed.), Aust. Acad. Sci., 129–136.

HUGHES, R.L. (1981). The influence of thermocline slope on equatorial thermocline displacement. **Dyn. Atmos. Oceans**, 5: 147–157.

HUGHES, R.L. (1981). A solution technique for deep baroclinic rotating flows. **Dyn. Atmos. Oceans**, 5: 159–173.

HUGHES, R.L. (1981). On cross-equatorial flow within a channel with application to the Makasar Strait. **Dyn. Atmos. Oceans**, 6: 103–120.

HUGHES, R.L. (1981). On inertial instability of the equatorial undercurrent. **Tellus**, 33: 291–300.

HUGHES, R.L. (1982). On a front between two rotating flows with application to the Flores Sea. **Dyn. Atmos. Oceans**, 6: 153–176.

HUGHES, R.L. (1983). The anti-cyclonic shear wave: A new geophysical wave. **J. Aust. Math. Soc.**, Ser. B. 25: 110–126.

HUGHES, R.L. and D.L.T. ANDERSON[1] (1984). On annual temperature variations in the main thermocline of the north Pacific Ocean. **J. Phys. Oceanogr.**, (in press).

HUGHES, R.L. and C. ZOPPOU[13] (1983). Virtual work in hydrostatics. **Int. J. Mech. Eng. Ed.**, 10: 195–197.

HUNT, B.G. (1971). A diffusive-photochemical study of the mesosphere and lower thermosphere and the associated conservation mechanisms. **J. Atmos. Terr. Phys.**, 33: 1869–1892.

HUNT, B.G. (1971). Cluster ions and nitric oxide in the D-region. **J. Atmos. Terr. Phys.**, 33: 929–942.

HUNT, B.G. (1972). Photochemical heating of the mesosphere and lower thermosphere. **Tellus**, 24: 47–55.

HUNT, B.G. (1973). A generalized aeronomic model of the mesosphere and lower thermosphere including ionospheric processes. **J. Atmos. Terr. Phys.**, 35: 1755–1798.

HUNT, B.G. (1973). Zonally symmetric global general circulation models with and without the hydrologic cycle. **Tellus**, 25: 337–354.

HUNT, B.G. (1974). A global general circulation model of the atmosphere based on the semi-spectral method. **Mon. Wea. Rev.**, 102: 3–16.

HUNT, B.G. (1976). Experiments with a stratospheric general circulation model: Part IV. Inclusion of the hydrologic cycle. **Mon. Wea. Rev.**, 104: 333–350.

HUNT, B.G. (1976). On the death of the atmosphere. **J. Geophys. Res.**, 81: 3677–3687.

HUNT, B.G. (1977). A simulation of the possible consequences of a volcanic eruption on the general circulation of the atmosphere. **Mon. Wea. Rev.**, 105: 247–260.

HUNT, B.G. (1978). Atmospheric vacillations in a general circulation model. I: The large-scale energy cycle. **J. Atmos. Sci.**, 35: 1133–1143.

HUNT, B.G. (1978). Atmospheric vacillations in a general circulation model. II: Tropospheric-stratospheric coupling and stratospheric variability. **J. Atmos. Sci.**, 35: 2052–2067.

HUNT, B.G. (1978). On the general circulation of the atmosphere without clouds. **Quart. J. Roy. Meteor. Soc.**, 104: 91–102.

HUNT, B.G. (1979). The effects of past variations of the Earth's rotation rate on climate. **Nature**, 281: 188–191.

HUNT, B.G. (1979). The influence of the Earth's rotation rate on the general circulation of the atmosphere. **J. Atmos. Sci.**, 36: 1392–1408.

HUNT, B.G. (1980). Numerical modelling of climate. **Aust. J. Phys.**, 33: 897–910.

HUNT, B.G. (1981). An evaluation of a sun-weather mechanism using a general circulation model of the atmosphere. **J. Geophys. Res.**, 86: 1233–1245.

HUNT, B.G. (1981). An examination of some feedback mechanisms in the carbon dioxide climate problem. **Tellus**, 33: 78–88.

HUNT, B.G. (1981). The maintenance of the zonal mean state of the upper atmosphere as represented in a three-dimensional general circulation model extending to 100 km. **J. Atmos. Sci.**, 38: 2172–2186.

HUNT, B.G. (1981). The 2-day wave in the middle atmosphere as simulated in a general circulation model extending from the surface to 100 km. **J. Atmos. Terr. Phys.**, 43: 1143–1154.

HUNT, B.G. (1982). An investigation with a general circulation model of the climatic effects of cloud albedo changes caused by atmospheric pollution. **J. Appl. Meteor.**, 21: 1071–1079.

HUNT, B.G. (1982). The impact of large variations of the Earth's obliquity on climate. **J. Meteor. Soc. Japan**, 60: 309–318.

HUNT, B.G. (1984). Polar glaciation and the genesis of ice ages. **Nature**, 308: 48–51.

HUNT, B.G. (1984). Some wave characteristics of the middle atmosphere simulated in a general circulation model extending from the surface to 100 km. **Quart. J. Roy. Meteor. Soc.**, 110: 187–202.

HUNT, B.G. and **N.C. WELLS** (1979). An assessment of the possible future climatic impact of carbon dioxide increases based on a coupled one-dimensional atmospheric-oceanic model. **J. Geophys. Res.**, 84: 787–791.

JOHNSON[10], D.R. and **W.K. DOWNEY** (1975). Azimuthally averaged transport and budget equations for storms: Quasi-Lagrangian diagnostics 1. **Mon. Wea. Rev.**, 103: 967–979.

JOHNSON[10], D.R. and **W.K. DOWNEY** (1975). The absolute angular momentum of storms: Quasi-Lagrangian diagnostics 2. **Mon. Wea. Rev.**, 103: 1063–1076.

JOHNSON[10], D.R. and **W.K. DOWNEY** (1976). The absolute angular momentum budget of an extratropical cyclone: Quasi-Lagrangian diagnostics 3. **Mon. Wea. Rev.**, 4: 3–14.

JOHNSON[10], D.R. and **W.K. DOWNEY** (1982). On the energetics of open systems. **Tellus**, 34: 458–470.

JOHNSON[15], J.A., C.B. FANDRY[4] and **L.M. LESLIE** (1971). On the variation of ocean circulation produced by bottom topography. **Tellus**, 23: 113–121.

KAROLY, D.J. (1982). Eliassen-Palm cross sections for the northern and southern hemispheres. **J. Atmos. Sci.**, 39: 178–182.

KAROLY, D.J. (1982). Atmospheric vacillations in a general circulation model. III. Analysis using transformed Eulerian-mean diagnostics. **J. Atmos. Sci.**, 39: 2916–2922.

KAROLY, D.J. (1983). Atmospheric teleconnections, forced planetary waves and blocking. **Aust. Met. Mag.**, 31: 51–56.

KAROLY, D.J. (1983). Rossby wave propagation in a barotropic atmosphere. **Dyn. Atmos. Oceans**, 7: 111–125.

KASAHARA[9], A. and **K. PURI** (1981). Spectral representation of three-dimensional global data by expansion in normal mode functions. **Mon. Wea. Rev.**, 109: 37–51.

KELLY, G.A.M. (1978). Interpretation of satellite cloud mosaics for southern hemisphere analysis and reference level specification. **Mon. Wea. Rev.**, 106: 870–889.

KELLY, G.A.M., G.A. MILLS and W.L. SMITH[16] (1978). Impact of Nimbus-6 temperature soundings on Australian region forecasts. **Bull. Amer. Meteor. Soc.**, 59: 393–405.

KELLY, G.A.M., B.W. FORGAN, P.E. POWERS and J.F. LE MARSHALL[6] (1982). Mesoscale observations from a polar orbiting satellite vertical sounder. In: **Nowcasting** (K.A. Browning, ed.), Academic Press. 107–121.

KELLY, G.A.M., B.W. FORGAN, P.E. POWERS, J.F. LE MARSHALL[6], M. HASSETT[6] and B. O'CONNOR[6] (1983). A satellite-based operational system for upper air analysis in the Australian region. **Rem. Sens. Envir.**, 13: 369–390.

LE MARSHALL[6], J.F. and **G.A.M. KELLY** (1981). A January and July climatology of the southern hemisphere based on daily numerical analyses 1973–1977. **Aust. Met. Mag.**, 29: 115–123.

LESLIE, L.M. (1971). The development of concentrated vortices: A numerical study. **J. Fluid Mech.**, 48: 1–21.

LESLIE, L.M. (1971). Implications of a direct method for solving the Helmholtz-type equations. **Aust. Met. Mag.**, 19: 130–134.

LESLIE, L.M. (1972). Comparative evaluation of fine-mesh limited-area grid schemes. **Aust. Met. Mag.**, 20: 1–21.

LESLIE, L.M. (1972). The wake of a finite rotating disc. **J. Aust. Math. Soc.**, XIII: 291–304.

LESLIE, L.M. (1979). On the correct formulation of semi-implicit schemes for grid-point models. **J. Meteor. Soc. Jap.**, 57: 465–468.

LESLIE, L.M. (1980). Numerical modelling of the summer heat low over Australia. **J. Appl. Meteor.**, 19: 381–387.

LESLIE, L.M. (1981). Comparative performance of convective parameterization schemes in a short-term prognosis model. **Beitr. Phys. Atmos.**, 54: 173–185.

LESLIE, L.M. and **B.J. McAVANEY** (1973). Comparative test of direct and iterative methods for solving Helmholtz-type equations. **Mon. Wea. Rev.**, 101: 235–239.

LESLIE, L.M. and R.K. SMITH[4] (1970). The surface boundary layer of a hurricane. II. **Tellus**, 22: 288–297.

LESLIE, L.M. and R.K. SMITH[4] (1977). On the choice of radial boundary conditions for numerical models of sub-synoptic vortex flows in the atmosphere with application to dust devils. **Quart. J. Roy. Meteor. Soc.**, 106: 499–510.

LESLIE, L.M. and R.K. SMITH[4] (1978). The effect of vertical stability on tornado genesis. **J. Atmos Sci.**, 35: 1281–1288.

LESLIE, L.M. and R.K. SMITH[4] (1982). Numerical studies of tornado structure and genesis. In: **Topics in Atmospheric and Oceanic Sciences**, Intense Atmospheric Vortices (M.J. Lighthill and L. Bengtsson, eds.), Springer-Verlag, 203–211.

LESLIE, L.M. and R.K. SMITH[4] (1984). A numerical study of tornadogenesis in a rotating thunderstorm II. **Quart. J. Roy. Meteor. Soc.**, 106: 544–548.

LESLIE, L.M., G.A. MILLS and **D.J. GAUNTLETT** (1981). The impact of FGGE data coverage and improved numerical techniques in numerical weather prediction in the Australian region. **Quart. J. Roy. Meteor. Soc.**, 107: 629–642.

LESLIE, L.M., B.R. MORTON[4] and R.K. SMITH[4] (1970). On modelling tornadoes. **Quart. J. Roy. Meteor. Soc.**, 96: 544–548.

McAVANEY, B.J. and **W. BOURKE** (1975). Southern hemisphere forecast experiments with a one-level spectral model. **J. Appl. Meteor.**, 14: 1011–1022.

McAVANEY, B.J. and **L.M. LESLIE** (1972). Comments on 'A direct solution of Poisson's equation by generalised sweep-out method'. **J. Meteor. Soc. Japan**, 50: 136–137.

McAVANEY, B.J., W. BOURKE and **K. PURI** (1978). A global spectral model for simulation of the general circulation. **J. Atmos. Sci.**, 35: 1557–1583.

McBRIDE, J.L. (1976). The effect of land-sea temperature contrast on short-term numerical forecasts. **Aust. Met. Mag.**, 23: 75–98.

McBRIDE, J.L. (1981). An analysis of diagnostic cloud mass flux models. **J. Atmos. Sci.**, 38: 1977–1990.

McBRIDE, J.L. (1983). It's an ill-wind that blows in the tropics. **Aust. Nat. Hist.**, 20: 405–411.

McBRIDE, J.L. (1982). Reply. **J. Atmos. Sci.**, 39: 2101–2103.

McBRIDE, J.L. (1983). Satellite observations of the southern hemisphere monsoon during Winter MONEX. **Tellus**, 35A: 189–197.

McBRIDE, J.L. (1984). Comments on 'Simulation of hurricane-type vortices in a general circulation model'. **Tellus**, (in press).

McBRIDE, J.L., and T.D. KEENAN[6] (1982). Climatology of tropical cyclone genesis in the Australian region. **J. Climatol.**, 2: 13–33.

McBRIDE, J.L. and **N. NICHOLLS** (1983). Seasonal relationships between Australian rainfall and the Southern Oscillation. **Mon. Wea. Rev.**, 111: 1998–2004.

McGREGOR, J.L. and **L.M. LESLIE** (1977). On the selection of grids for semi-implicit schemes. **Mon. Wea. Rev.**, 105: 236–238.

McGREGOR, J.L., L.M. LESLIE and **D.J. GAUNTLETT** (1978). The ANMRC limited-area model: Consolidated formulation and operational results. **Mon. Wea. Rev.**, 106: 427–438.

MAINE, R. (1969). A real-time interactive control system for meteorological operations. **J. Appl. Meteor.**, 8: 845–853.

MAINE, R. (1972). A filtered-equation model for operations and research. **J. Appl. Meteor.**, 11: 7–15.

MALONE[17], R.C., E.J. PITCHER[18], M.L. BLACKMON[19], **K.K. PURI** and **W.P. BOURKE** (1984). The simulation of stationary and transient geopotential-height eddies in January and July with a spectral general circulation model. **J. Atmos. Sci.**, 41: 1394–1419.

MILLER[19], A.J. and **L.M. LESLIE** (1984). Single-station forecasting of cloud cover and precipitation up to 12 hours ahead. **Mon. Wea. Rev.**, 112: 1198–1205.

MILLS, G.A. (1977). A data impact study using constant level balloon data in southern hemisphere analyses and prognoses. **Aust. Met. Mag.**, 25: 151–169.

MILLS, G.A. (1981). An objective limited-area analysis/prognosis experiment using FGGE data in the Australian region. **Mon. Wea. Rev.**, 109: 1898–1913.

MILLS, G.A. (1983). The sensitivity of a numerical prognosis to moisture detail in the initial state. **Aust. Met. Mag.**, 31: 111–119.

MILLS, G.A., C.M. HAYDEN[20] (1984). The use of high horizontal resolution satellite temperature and moisture profiles to initialize a mesoscale numerical weather prediction model: A severe weather event case study. **J. Climatol. Appl. Meteor.**, (in press).

MILLS, G.A. and **J.L. McGREGOR** (1983). Vertical mode initialization in a limited area data assimilation experiment. **Mon. Wea. Rev.**, 111: 2110–2121.

MIYAKODA[21], K., T. GORDON[21], R. CAVERLY[21], W. STERN[21], J. SIRUTIS[21] and **W. BOURKE** (1983). Simulation of a blocking event in January 1977. **Mon. Wea. Rev.**, 111: 846–869.

NICHOLLS, N. (1977). Tropical-extratropical interactions in the Australian region. **Mon. Wea. Rev.**, 105: 826–832.

NICHOLLS, N. (1978). Air-sea interaction and the quasi-biennial oscillation. **Mon. Wea. Rev.**, 106: 1505–1508.

NICHOLLS, N. (1978). Comment on the paper 'On the application of some stochastic models to precipitation forecasting' by T.G.J. Dyer. **Quart. J. Roy. Meteor. Soc.**, 104: 228–230.

NICHOLLS, N. (1978). Sunspots and Australian wheat yield. **Search**, 9: 319.

NICHOLLS, N. (1979). A possible method for predicting seasonal tropical cyclone activity in the Australian region. **Mon. Wea. Rev.**, 107: 1221–1224.

NICHOLLS, N. (1979). A simple air-sea interaction model. **Quart. J. Roy. Meteor. Soc.**, 105: 93–105.

NICHOLLS, N. (1980). Long-range weather forecasting: Value, status, and prospects. **Rev. Geophys. Sp. Phys.**, 18: 771–788.

NICHOLLS, N. (1981). Air-sea interaction and the possibility of long-range weather prediction in the Indonesian archipelago. **Mon. Wea. Rev.**, 109: 2435–2443.

NICHOLLS, N. (1981). Sunspot cycles and Australian rainfall. **Search**, 12: 83–85.

NICHOLLS, N. (1983). The potential for long-range prediction of seasonal mean temperature in Australia. **Aust. Met. Mag.**, 31: 203–207.

NICHOLLS, N. (1983). Predictability of the 1982 Australian drought. **Search**, 14: 154–155.

NICHOLLS, N. (1983). Predicting Indian monsoon rainfall from sea-surface-temperature in the Indonesia — north Australia area. **Nature**, 307: 576–577.

NICHOLLS, N. (1983). Reply. **Aust. Met. Mag.**, 31: 65–66.

NICHOLLS, N. (1984). The stability of empirical long-range forecast techniques: A case study. **J. Clim. Appl. Meteor.**, 23: 143–147.

NICHOLLS, N. (1984). The Southern Oscillation and Indonesian sea surface temperature. **Mon. Wea. Rev.**, 112: 424–432.

NICHOLLS, N. (1984). Comments on 'The Monsson of East Asia and its global associations'. **Bull. Amer. Meteor. Soc.**, (in press).

NICHOLLS, N. (1984). A system for predicting the onset of the north Australian wet-season. **J. Climatol.**, (in press).

NICHOLLS, N. (1984). Southern Oscillation, sea-surface-temperature, and interannual fluctuations in Australian tropical cyclone activity. **J. Climatol.**, (in press).

NICHOLLS, N., and F. WOODCOCK[6] (1981). Verification of an empirical long-range weather forecasting technique. **Quart. J. Roy. Meteor. Soc.** 107: 973–976.

NICHOLLS, N., G.V. GRUZA[28], Y. KIKUCHI[29] and R. SOMERVILLE[30] (1984). Long-range weather forecasting: recent research. WMO Programme on Weather Prediction Research. Long-Range Forecasting Research Publications Series No. 3, 58 pp.

NICHOLLS, N., J.L. McBRIDE and **R.J. ORMEROD** (1982). On predicting the onset of the Australian wet season at Darwin. **Mon. Wea. Rev.**, 110: 14–17.

PASCOE[22], D.J. and **B.W. FORGAN** (1980). An investigation of the Linke-Feussner pyrheliometer temperature coefficient. **Solar Energy**, 25: 191–192.

PITCHER[18], E.J., R.C. MALONE[17], V. RAMANATHAN[9], M.L. BLACKMON[9], **K. PURI** and **W. BOURKE** (1983). January and July simulations with a spectral general circulation model. **J. Atmos. Sci.**, 40: 580–604.

PITTOCK[2], A.B., P.J.B. FRASER[2], I.E. GALBALLY[2], P. HYSON[2], R.N. KULKARNI[2], G.I. PEARMAN[2], E.K. BIGG[24] and **B.G. HUNT** (1981). Human impact on the global atmosphere: Implications for Australia. **Search**. 12: 260–272.

PRICE[6], P.G. and **N. NICHOLLS** (1982). Southern hemisphere energetics: a reappraisal of some earlier estimates. **Tellus**, 34: 406–408.

PURI, K. (1981). Extended-range forecasts for the southern hemisphere with the ANMRC spectral model. **Mon. Wea. Rev.**, 109: 286–305.

PURI, K. (1981). Local geostrophic wind correction in the assimilation of height data and its relationship to the slow manifold. **Mon. Wea. Rev.**, 109: 52–55.

PURI, K. (1983). Normal mode initialization for the ANMRC spectral model. **Aust. Met. Mag.**, 31: 85–95.

PURI, K. (1983). The relationship between convective adjustment, Hadley circulation and normal modes of the ANMRC spectral model. **Mon. Wea. Rev.**, 111: 23–33.

PURI, K. (1983). Some experiments in variational normal mode initialization in data assimilation. **Mon. Wea. Rev.**, 111: 1208–1218.

PURI, K. (1984). Sensitivity of low latitude velocity potential field in a numerical model to initial conditions, initialization and physical processes. **Mon. Wea. Rev.** (in press).

PURI, K. and **W. BOURKE** (1974). Implications of horizontal resolution in spectral model integrations. **Mon. Wea. Rev.**, 102: 333–347.

PURI, K. and **W. BOURKE** (1982). A scheme to retain the Hadley circulation during non-linear normal mode initialization. **Mon. Wea. Rev.**, 110: 327–335.

PURI, K., W. BOURKE and **R. SEAMAN** (1982). Incremental linear normal mode initialization in four-dimensional assimilation. **Mon. Wea. Rev.**, 110: 1773–1785.

RADOK[13], U., **N.A. STRETEN** and G.E. WELLER[24] (1975). The Southern Ocean: Atmosphere and ice. **Oceanus**, 18: 16–27.

RYAN[23], B.F. and **N.E. DAVIDSON** (1984). Isentropic relative flow analysis of an extra tropical cyclone: Diagnosis of cloud and rainfall. **Quart. J. Roy. Meteor, Soc.**, (in press).

SEAMAN, R.S. (1969). Experiments with the omega equation in the Australian region. **Aust. Met. Mag.**, 17: 177–197.

SEAMAN, R.S. (1972). Stability-temperature correlations and their application to objective analysis. **Aust. Met. Mag.**, 20: 83–104.

SEAMAN, R.S. (1973). Analysis accuracy achievable with specified observational networks. **Aust. Met. Mag.**, 21: 93–111.

SEAMAN, R.S. (1975). Distance-time autocorrelation functions for winds in the Australian region. **Aust. Met. Mag.**, 23: 27–40.

SEAMAN, R.S. (1976). Statistically based 250 mb wind forecasts. **Aust. Met. Mag.**, 24: 149–163.

SEAMAN, R.S. (1977). Absolute and differential accuracy of analyses achievable with specified observational network characteristics. **Mon. Wea. Rev.**, 105: 1211–1222.

SEAMAN, R.S. (1982). A systematic description of the spatial variability of geopotential and temperature in the Australian region. **Aust. Met. Mag.**, 30: 133–141.

SEAMAN, R.S. (1982). Comments on 'Space and time scales of atmospheric variability'. **J. Atmos. Sci.**, 39: 925–927.

SEAMAN, R.S. (1983). Objective analysis accuracies of statistical interpolation and successive correction schemes. **Aust. Met. Mag.**, 31: 225–240.

SEAMAN, R.S. and **F.J. GAUNTLETT** (1980). Directional dependence of zonal and meridional wind correlation coefficients. **Aust. Met. Mag.**, 28: 217–221.

SEAMAN, R.S. and **F. J. GAUNTLETT** (1982). A quantitative comparison of variations on isobaric and isentropic surfaces in the Australian region. **Aust. Met. Mag.**, 30: 273–277.

SEAMAN, R.S. and C.M. HAYDEN[20] (1979). Application of quantitative satellite data to numerical analysis and prediction. **W.M.O. Tech. Note**, 166: 87–102.

SEAMAN, R.S., R.L. FALCONER[6] and J. BROWN[6] (1978). Application of a variational blending technique to numerical analysis in the Australian region. **Aust. Met. Mag.**, 25: 3–23.

SIMPSON, R.W. and **W.K. DOWNEY** (1975). The effect of a warm mid-latitude sea surface temperature anomaly on a numerical simulation of the general circulation of the southern hemisphere. **Quart. J. Roy. Meteor. Soc.**, 101: 847–867.

SKINNER[6], T.C.L. and **L.M. LESLIE** (1982). Predictability experiments with the Australian west coast summer trough. **Aust. Met. Mag.**, 30: 241–249.

SMITH[4], R.K. and **L.M. LESLIE** (1976). Thermally driven vortices: A numerical study with applicaton to dust-devil dynamics. **Quart. J. Roy. Meteor. Soc.**, 102: 791–804.

SMITH[4], R.K. and **L.M. LESLIE** (1979). A numerical study of tornadogenesis in a rotating thunderstorm. **Quart. J. Roy. Meteor. Soc.**, 105: 107–127.

SMITH[4], R.K. and **L.M. LESLIE** (1978). Tornadogenesis. **Quart. J. Roy. Meteor. Soc.**, 104: 189–199.

SMITH[4], R.K., J.V. MANSBRIDGE and **L.M. LESLIE** (1977). Comments on 'Effect of precipitation-driven downdraft on a rotating wind field: A possible trigger mechanism for tornadoes?' **J. Atmos. Sci.**, 34: 548–549.

SMITH[4], R.K., B.R. MORTON[4] and **L.M. LESLIE** (1975). The role of dynamic pressure in generating fire wind. **J. Fluid Mech.**, 68: 1–19.

STRETEN, N.A. (1969). A note on the frequency of closed circulations between 50°S and 70°S in summer. **Aust. Met. Mag.**, 17: 228–234.

STRETEN, N.A. (1969). Aspects of winter temperatures in interior Alaska. **Arctic**, 22: 403–412.

STRETEN, N.A. (1970). A note on the climatology of the satellite observed zone of high cloudiness in the central South Pacific. **Aust. Met. Mag.**, 18: 31–38.

STRETEN, N.A. (1973). Satellite observations of the summer decay of the Antarctic sea-ice. **Arch. Met. Geoph. Biokl.**, Ser. A, 22: 119–134.

STRETEN, N.A. (1973). Some characteristics of satellite-observed bands of persistent cloudiness over the southern hemisphere. **Mon. Wea. Rev.**, 101: 486–495.

STRETEN, N.A. (1974). A satellite view of weather systems over the North American Arctic. **Weather**, 29: 369–380.

STRETEN, N.A. (1974). VHRR — a new environmental data source for Alaska. **Northern Engineer**, 6: 21–24.

STRETEN, N.A. (1974). Large-scale sea ice features in the western Arctic basin and the Bering Sea as viewed by the NOAA-2 satellite. **Arctic and Alpine Res.**, 6: 333–345.

STRETEN, N.A. (1974). Some features of the summer climate of interior Alaska. **Arctic**, 27: 273–286.

STRETEN, N.A. (1975). Cloud cell size and pattern evolution in Arctic air advection over the North Pacific. **Arch. Met. Geoph. Biokl.**, Ser. A, 24: 213–228.

STRETEN, N.A. (1975). Satellite derived inferences to some characteristics of the South Pacific atmospheric circulation associated with the Nino event of 1972–73. **Mon. Wea. Rev.**, 103: 989–995.

STRETEN, N.A. (1975). Satellite studies of the atmospheric circulation of the southern hemisphere. In: **Climate of the Arctic** (G. Weller and S.A. Bowling, eds.), Geophys. Inst., Univ. Alasks, Fairbanks, Alaska, 181–189.

STRETEN, N.A. (1977). Aspects of the year-to-year variation of seasonal and monthly mean station temperature over the southern hemisphere. **Mon. Wea. Rev.**, 105: 195–205.

STRETEN, N.A. (1977). Seasonal climatic variability over the southern oceans. **Arch. Met. Geoph. Biokl.**, Ser. B, 25: 1–19.
STRETEN, N.A. (1978). A quasi-periodicity in the motion of the South Pacific cloud band. **Mon. Wea. Rev.**, 106: 1211–1214.
STRETEN, N.A. (1978). Satellite observed cloud in relation to sea surface temperature patterns in the Western Australian region. **Aust. Met. Mag.**, 26: 1–17.
STRETEN, N.A. (1979). A cross-hemisphere cloud line phenomenon. **Mon. Wea. Rev.**, 107: 215–218.
STRETEN, N.A. (1980). Antarctic meteorology: The Australian contribution past, present and future. **Aust. Met. Mag.**, 28: 105–140.
STRETEN, N.A. (1980). Some synoptic indices of the southern hemisphere mean sea level circulation 1972–1977. **Mon. Wea. Rev.**, 108: 18–36.
STRETEN, N.A. (1981). Southern hemisphere sea surface temperature variability and apparent associations with Australian rainfall. **J. Geophys. Res.**, 86: 485–497.
STRETEN, N.A. (1982). Exploring southern hemisphere climates. **Aust. Met. Mag.**, 30: 143–153.
STRETEN, N.A. (1983). Circulation contrasts in the southern hemisphere winters of 1972 and 1973. **Aust. Met. Mag.**, 31: 161–170.
STRETEN, N.A. (1983). Extreme distributions of Australian rainfall in relation to sea surface temperature. **J. Climatol.**, 143–153.
STRETEN, N.A. (1983). High latitude climates of the Pacific — past, present and future. **Aust. Met. Mag.**, 31: 179–197.
STRETEN, N.A. (1983). Antarctic sea ice and related atmospheric circulation during FGGE. **Arch. Met. Geoph. Biokl.**, Ser. A. 32: 231–246.
STRETEN, N.A. and **W.K. DOWNEY** (1977). Defence Meteorological Satellite Program (DMSP) imagery: A research tool for the Australian region. **Aust. Met. Mag.,** 25: 25–36.
STRETEN, N.A. and **W.R. KELLAS** (1973). Aspects of cloud pattern signatures of depressions in maturity and decay. **J. Appl. Meteor.**, 12: 23–27.
STRETEN, N.A. and **W.R. KELLAS** (1975). Some applications of simple image analysis techniques to very high resolution satellite data. **Aust. Met. Mag.,** 23: 7–20.
STRETEN, N.A. and **D.J. PIKE** (1980). Characteristics of the broadscale Antarctic sea ice extent and the associated atmospheric circulation 1972–1977. **Arch. Met. Geoph. Biokl.**, Ser. A, 29: 279–299.
STRETEN, N.A. and **D.J. PIKE** (1980). Indices of the mean monthly surface circulation over the southern hemisphere during FGGE. **Aust. Met. Mag.**, 28: 201–215.
STRETEN, N.A. and A.J. TROUP[2] (1973). A synoptic climatology of satellite observed cloud vortices over the southern hemisphere. **Quart. J. Roy. Meteor. Soc.**, 99: 56–72.
STRETEN, N.A. and **N.C. WELLS**. (1977). Atmospheric and oceanic circulation at high latitudes of the South Atlantic and southwest Indian oceans. **Deep Sea Res.**, 24: 791–793.
STRETEN, N.A. and J.W. ZILLMAN[6] (1984). The climate of the South Pacific Ocean. In: **Climates of the Oceans** (H. van Loon, ed.), Elsevier.
STRETEN, N.A., N. ISHIKAWA[24] and G. WENDLER[24] (1974). Some observations of the local wind regime on an Alaskan Arctic glacier. **Arch. Met. Geoph. Biokl.**, Ser. B, 22: 337–350.
THURLING, R.L. (1981). Numerical modelling of the atmosphere — a systems view. **Aust. Comp. Bull.**, 5: 22–29.
TROUP[2], A.J. and **N.A. STRETEN** (1972). Satellite-observed southern hemisphere cloud vortices in relation to conventional observations. **J. Appl. Meteor.**, 11: 909–917.
TSUCHIYA[11], T. and **W.K. DOWNEY** (1981). A case study evaluation of 'GMS winds' in the Australian region. **Aust. Met. Mag.**, 29: 89–98.
TUCKER, G.B. (1969). Numerical models of the earth's atmosphere. **Aust. Physicist**, 6: 179–182.

TUCKER, G.B. (1971). Focus on southern hemisphere problems in dynamical meteorology. **W.M.O. Bull.**, 20: 232–237.

TUCKER, G.B. (1974). Vertical velocities and vertical eddy fluxes derived from serial soundings at one station. **Quart. J. Roy. Meteor. Soc.**, 99: 520–539.

VOICE, M.E. (1970). A method of obtaining a surface pressure forecast derived from the barotropic model. **Aust. Met. Mag.**, 18: 159–176.

VOICE, M.E. (1983). Drought in Australia. **Aust. Nat. Hist.**, 20: 3–9.

VOICE, M.E. and **F.J. GAUNTLETT** (1984). Ash Wednesday fires in Australia. **Mon. Wea. Rev.**, 112:584–590.

VOICE, M.E. and **B.G. HUNT** (1975). Southern hemisphere forecasting experiments with a semi-spectral model. **Mon. Wea. Rev.**, 103: 1077–1088.

VOICE, M.E. and **B.G. HUNT** (1984). A study of the dynamics of drought initiation using a global general circulation model. **J. Geophys. Res.**, (in press).

VOICE, M.E., U. RADOK[13], D. JENSSEN[13] and the late J. BAYLISS[13] (1972). A barotropic numerical weather prediction experiment for the Australian region. **Aust. Met. Mag.**, 20: 129–173.

WEBSTER, P.J. (1972). The response of the tropical atmosphere to local steady forcing. **Mon. Wea. Rev.**, 100: 518–541.

WEBSTER, P.J. (1973). Remote forcing of the time-independent tropical atmosphere. **Mon. Wea. Rev.**, 101: 58–68.

WEBSTER, P.J. and **N.A. STRETEN** (1972). Aspects of Late Quaternary climate in tropical Australia. In: **Bridge and Barrier: The Natural and Cultural History of Torres Strait** (D. Walker, ed.), Research School of Pacific Studies, A.N.U., Canberra. Publication BG/3: 39–60.

WEBSTER[2], P.J. and **N.A. STRETEN** (1978). Late-Quaternary ice age climates of tropical Australasia: Interpretations and reconstructions. **Quaternary Res.**, 10: 279–309.

WELLS, N.C. (1979). A coupled ocean-atmosphere experiment: The ocean response. **Quart. J. Roy. Meteor. Soc.**, 105: 355–370.

WELLS, N.C. (1979). The effect of a tropical sea surface temperature anomaly in a coupled ocean-atmosphere model. **J. Geophys. Res.**, 84: 4971–4984.

WELLS, N.C. and **K.K. PURI** (1979). Atmospheric feedback in a coupled ocean-atmosphere model. **J. Geophys. Res.**, 84: 4985–4997.

WENDLER[24], G., N. ISHIKAWA[24] and **N.A. STRETEN** (1974). The climate of the McCall Glacier, Brooks Range, Alaska, in relation to its geographical setting. **Arctic Alp. Res.**, 6: 307–318.

WILLSON, M.A.G. (1975). A wavenumber frequency analysis of large-scale tropospheric motions in the extratropical northern hemisphere. **J. Atmos. Sci.**, 32: 478–488.

WILLSON, M.A.G. (1975). Atmospheric tidal motions over Australia below 20 kilometres. **Mon. Wea. Rev.**, 103: 1110–1120.

WOODCOCK[6], F. and **N. NICHOLLS** (1982). A methodology for numerical prognosis evaluation using objective local weather retrieval. **Aust. Met. Mag.**, 30: 155–161.

Conference Papers

BARKER, A.A. Convection studies with a general circulation model. Abstracts IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, DC–7.

BARKER, A.A. and **W.R. KININMONTH.** A cloud model to parameterize convection. WMO/IAMAP Symposium Digest on Mesoscale Meteorological Systems and Fine Mesh Modelling, May 14–18, 1973, Shinfield Park, Reading, Berks., UK.

BOURKE, W.P. A primitive equation spectral model. Proceedings of the (ninth) Stanstead Seminar, July 12–16, 1971, Quebec, Canada, Publication in Meteorology No. 103, McGill University, 1972, 49–51.

BOURKE, W.P. A multi-level spectral model. Abstracts, IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, GARP–II–1.

BOURKE, W.P., K. PURI and **R. THURLING.** Numerical prediction for the southern hemisphere via the spectral method. Report of the International Symposium on Spectral Methods in Numerical Weather Prediction, Copenhagen, 12–16 August 1974, GARP Programme on Numerical Experimentation, Report No. 7, 1974, 22–42.

BOURKE, W.P., R. SEAMAN and **K. PURI.** Assimilation analysis, prognosis and data impact in the southern hemisphere during SOP–2. WMO International Conference on Preliminary FGGE Data Analysis and Results, 23–27 June 1980, Bergen, Norway, ICSU/WMO, 140–149.

BOURKE, W.P., B.J. McAVANEY, K.K. PURI, R.S. SEAMAN and **L.W. LOGAN.** Assimilation experiments with southern hemisphere data from the second Special Observing Period. Preprints, Australia — New Zealand GARP Symposium, December 17–19, Melbourne, Australia, 41.

CARPENTER[27], D.J. and **B.W. FORGAN.** Atmospheric radiance correction for ocean colour remote sensing. Extended Abstracts, 1st Australasian Conference on the Physics of Remote Sensing of Atmosphere and Ocean, 13–16 February 1984, Melbourne, Australia, 130–132.

DALEY[9] R. and **K.K. PURI.** The application of normal mode analysis to four-dimensional data assimilation. 13th Annual Congress Canadian Meteorological and Oceanographic Society, 30 May — 1 June 1979, University of Victoria, British Columbia, Canada, 37.

DAVIDSON, N.E. Short term active and break phases of Australia's monsoon during WMONEX. Extended Abstracts, Australian Conference of Tropical Meteorology, 24–25 March 1983, Melbourne, Bureau of Meteorology and Roy. Meteor. Soc. Aust. Br., 1–3.

DAVIDSON, N.E. Active and break phases of Australia's monsoon during Winter MONEX: Large scale convective variations. Preprints, 15th Technical Conference on Hurricanes and Tropical Meteorology, 9–13 January 1984, Miami. Fla., Amer. Meteor. Soc.

DAVIDSON, N.E. Diurnal variation of cloud cluster aggregates and the tropical wind field in the Australian monsoon. Abstracts, International Conference on Mesoscale Meteorology, 6–10 February 1983, Melbourne, 33.

DAVIDSON, N.E., J.L. McBRIDE and **B.J. McAVANEY.** The onset of the Australian monsoon during Winter MONEX. Extended Abstracts and Panel Session, International Conference on the Scientific Results of the Monsoon Experiment, 26–30 October 1981, Denpasar, Bali, Indonesia, 5:17–20.

DOWNEY, W.K. A lecture on 'The energetics of open systems'. Conference Handbook, Two Day Workshop on Fronts, May 26–27, 1977, Melbourne, Bureau of Meteorology, Roy. Meteor. Soc. Aust. Br., 8.

DOWNEY, W.K. Cyclone Wanda and the Brisbane floods of 1974: Implications for cyclone modification programs. Abstracts, International Conference on Tropical Cyclones, 25–29 November 1979, Perth, Australia, Roy. Meteor. Soc. Aust. Br., Amer. Meteor. Soc., and Aust. Acad. Sci.

DOWNEY, W.K. and **N.A. STRETEN.** The use of temporarily frequent high resolution satellite imagery for meso-scale analysis and trend forecasting. AIRMET Papers, Papers and Discussion from the AIRMET Conference, 9–10 February 1978, Canberra, Canberra Meteor. Soc., and Roy. Meteor. Soc. Aust. Br., 17–26,

DOWNEY, W.K., T. TSUCHIYA[11] and P.F. NOAR[6]. A case study of the northwest Australian cloud band (NAC) during Special Observing Period II of the First GARP Global Experiment. Preprints, Australia — New Zealand GARP Symposium, December 17–19, Melbourne, Australia, 79.

FANDRY, C. Wind-driven and tidal circulation in Bass Strait. Meeting of Australian Physical Oceanographers, March 2–5, 1981, CSIRO Cronulla, CSIRO Division of Fisheries and Oceanography, 4.

FANDRY, C.B. Wind-driven transient motion on the Bass Strait continental shelf. Workshop on Transient Circulation on Continental Shelves, December 1982, Monterey, California.

FANDRY, C.B. A two-layer quasi-geostrophic model of the west coast trough. Abstracts, Australian Applied Mathematics Conference, February 1983, Perth.

FANDRY, C.B. A numerical model of the Bass Strait wind-driven and tidal circulation. VIMS Workshop on Hydrodynamic Modelling, February 1983, Melbourne.

FANDRY[4], C.B. and **L.M. LESLIE.** On the variation of ocean circulation produced by bottom topography. Contributions to the International Marine Science Symposium, 1971, Institute of Marine Sciences, University of N.S.W., Sydney, Australia, 112.

FORGAN, B.W. Achievable pyranometric accuracies. Solar and Wind Data Network for Australia, 19–20 October 1981, Canberra, Solar Energy Research Institute, W.A., 191–192.

GAUNTLETT, D.J. The numerical simulation of intense frontal discontinuities over south eastern Australia. Proceedings, IAMAP Symposium, Nowcasting: Mesoscale Observations and Short-Range Prediction. 25–28 August 1981, Hamburg, Federal Republic of Germany, Eur. Space Agency SP–165, 271–275.

GAUNTLETT, D.J. The problem of meso-scale numerical weather prediction. Abstracts, Australian Conference on Applied Mathematics, February 1983, Perth.

GAUNTLETT, D.J. and **L.M. LESLIE.** Comparative explicit/semi-implicit time integration. WMO/IAMAP Symposium Digest on Mesoscale Meteorological Systems and Fine Mesh Modelling, May 14–18, 1973, Shinfield Park, Reading, Berks., UK.

GAUNTLETT, D.J. and **L.M. LESLIE.** On the predictability of Southerly Busters. Programme and Abstracts, IAMAP General Assembly, IUGG XVIII General Assembly, 15–27 August 1983, Hamburg, Federal Republic of Germany, 137.

GAUNTLETT, D.J. and **R.S. SEAMAN.** Four-dimensional analysis experiments in the southern hemisphere. Abstracts, IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, GARP–II–5.

GAUNTLETT, D.J., L.M. LESLIE. and **G.A. MILLS.** Recent developments in the regional application of NWP in Australia. Preprints, Fourth Conference on Numerical Weather Prediction, October 29 — November 1, 1979, Silver Spring, Md., Amer. Meteor. Soc., 313–318.

GAUNTLETT, D.J., L.M. LESLIE., D.R. HICKSMAN and **T.F. HALES.** The ANMRC limited area numerical weather prediction model. Preprints, Sixth Conference on Weather Forecasting and Analysis, May 10–14, 1976, Albany, NY, Amer. Meteor. Soc., 117–120.

GAUNTLETT, D.J., L.M. LESLIE., J.L. McGREGOR and **D.R. HINCKSMAN.** Recent results from the ANMRC limited area nested model. International Conference on large Scale Simulation of the Atmosphere, August 30 — September 4, 1976, Hamburg, Federal Republic of Germany, Deutsche Meteor. Gesellschaft and Amer. Meteor. Soc., 169–172.

HUGHES, R. Random behaviour in the oceanic mixed layer — a climatic study ANMRC. Abstracts, Meeting of Australian Physical Oceanographers, 30–31 August 1979, CSIRO Cronulla, CSIRO Division of Fisheries and Oceanography, 23.

HUGHES, R.L. On the dynamics of the Celebes and Sulu seas. Conference on Hydraulics and Fluid Mechanics, 18–22 August 1980, Brisbane, Institute of Engineers, Australia.

HUGHES, R. On the circulation at the intersection of the Macassar Strait and Flores Sea during the south-east monsoon. Meeting of Australian Physical Oceanographers, March 2–5, 1981, CSIRO Cronulla, CSIRO Division of Fisheries and Oceanography, 18.

HUNT, B.G. Preliminary results of an upper atmospheric general circulation model. Proceedings of the International Conference on Structure, Composition and General Circulation of the Upper and Lower Atmospheres and Possible Anthropogenic Perturbations, January 14–25, 1974, Melbourne, Australia, Vol. II, 764–776.

HUNT, B.G. Some possible photochemical and modelling implications of a very dry stratosphere obtained with a general circulation model. Proceedings of the International Conference on Structure, Composition and General Circulation of the Upper and Lower Atmospheres and Possible Anthropogenic Perturbations, January 14–25, 1974, Melbourne, Australia, Vol. II, 871–880.

HUNT, B.G. Problems and prospects for sun-weather relations. Discussion Meeting on Solar-Terrestrial Physics, 29–30 August 1980, La Trobe University, National Committee for Solar-Terrestrial Physics, Aust. Acad. Sci., 224–237.

HUNT, B.G. Meteorological coupling of the middle atmosphere. Discussion meeting on Solar-Terrestrial Physics, 29–30 August 1980, La Trobe University, National Committee for Solar-Terrestrial Physics, Aust. Acad. Sci., 238.

HUNT, B.G. Problems associated with modelling CO_2 induced climatic changes, particularly feedback mechanisms. The Carbon Dioxide Climate Problem, 15–17 September 1980, Canberra. In: Carbon Dioxide and Climate: Australian Research (G.I. Pearman, ed.), Aust. Acad. Sci., 183.

HUNT, B.G. A simulation of the polar meteorology of the upper atmosphere. Preprints, Antarctica: Weather and Climate, 11–13 May 1981, University of Melbourne, Parkville, Vic., Aust., Roy. Meteor. Soc. Aust. Br., compiled by N.W. Young.

HUNT, B.G. Three dimensional dynamical and photochemical modelling of the middle atmosphere. Programme and Abstracts, IUGG Inter-disciplinary Symposia, IUGG XVIII General Assembly, 15–27 August 1983, Hamburg, Federal Republic of Germany, 657.

KAROLY, D.J. The steady, linear response of the upper atmosphere to tropospheric forcing. Proceedings, IAMAP Symposium on the Middle Atmospheric Sciences, 17–22 August 1981, Hamburg, Federal Republic of Germany.

KAROLY, D.J. and B.J. HOSKINS[25]. Three dimensional propagation of planetary waves. Proceedings, IAMAP Symposium on the Middle Atmospheric Sciences, 17–22 August 1981, Hamburg, Federal Republic of Germany.

KAROLY[4], D.J., **G.A.M. KELLY** and J.F. LE MARSHALL[6]. Interannual variability of the southern hemisphere troposphere. Preprints, First International Conference on Southern Hemisphere Meteorology, July 31–August 6, 1983, Sao Jose Dos Campos, Brazil, Amer. Meteor. Soc., 44–46.

KASAHARA[9], A. and **K.K. PURI.** Spectral representation of three-dimensional global data in terms of normal mode functions. Preprints, Fourth Conference on Numerical Weather Prediction, October 29–November 1, 1979, Silver Spring, Md., Amer. Meteor, Soc., 168–171.

KELLY, G. A method for using satellite cloud mosaic data and satellite vertical temperature soundings for numerical analysis. Abstracts, IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, GARP–IV–5.

KELLY, G.A.M. A southern hemisphere analysis/forecast cycling experiment using satellite data. Proceedings of the Symposium on Meteorological Observations from Space: Their Contribution to the First GARP Global Experiment, June 8–10, 1976, Philadelphia, Penna., USA, COSPAR, 413.

KELLY, G.A. and J.F. LE MARSHALL[6]. The Australian operational direct readout and TOVS processing system and its application to the Tasman Sea intercomparison study. The Technical Proceedings of the First International TOVS Study Conference, Igls, Austria, 29 August — 2 September 1983, W.P. Menzel, ed. A Report from the CIMSS, Space Science Engineering Center, University of Wisconsin, 1984, 111–131.

KELLY, G.A.M., P.E. POWERS and **F.J. GAUNTLETT.** Temperature and water vapour retrievals from the NOAA 4 satellite in the southern hemisphere. Proceedings of the Symposium on Meteorological Observations from Space: Their Contribution to the First GARP Global Experiment, June 8–10, 1976, Philadelphia, Penna., USA, COSPAR, 77–84.

KELLY, G., P.E. POWERS and T. HART[6]. Use of statistical methods for producing operational temperature retrievals in the Australian region from TOVS data. Extended Abstracts, 1st Australian Conference on the Physics of Remote Sensing of Atmosphere and Ocean, 13–16 February 1984, Melbourne, 40–44.

KELLY, G.A., B.W. FORGAN, P.E. POWERS and J. LE MARSHALL[6]. The use of direct readout TOVS (TIROS Operational Vertical Sounder) data from TIROS–N and NOAA–6 spacecraft to study a cut-off low and associated mesoscale cold pools. Proceedings, IAMAP Symposium, Nowcasting: Mesoscale Observations and Short-Range Prediction, 25–28 August 1981, Hamburg, Federal Republic of Germany, Eur. Space Agency SP–165, 89–98.

KININMONTH, W.R. A parameterization of the heat exchange between convective clouds and the synoptic scale flow. Proceedings, International Conference on Weather Modification, September 6–11, 1971, Canberra, Australia. Aust. Acad. Sci and Amer. Meteor. Soc., 313–318.

LE MARSHALL[6], J.F., **G.A.M. KELLY** and D.J. KAROLY[4]. A climatology of the southern hemisphere based on 10 years of daily numerical analyses. Preprints, First International Conference on Southern Hemisphere Meteorology, July 31–August 6, 1983, Sao Jose Dos Campos, Brazil, Amer. Meteor. Soc., 41–43.

LESLIE, L. and **C.B. FANDRY.** A two-layer model of summer trough formation over the Australian continent. Extended Abstracts, Australian Conference on Tropical Meteorology, 24–25 March 1983, Melbourne, Bureau of Meteorology and Roy. Meteor. Soc. Aust. Br., 35–36.

LESLIE, L.M. and **D.J. GAUNTLETT.** The influence of summer ground radiative heating on numerical weather prediction. Second Australasian Conference on Heat and Mass Transfer, February 16–18, 1977, University of Sydney, N.S.W., Australia, 137–144.

LESLIE, L.M. and B.R. MORTON[4]. Convective stagnation under an inversion — a numerical experiment. First Australasian Conference on Heat and Mass Transfer, May 23, 24, 25, 1973, Monash University, Melbourne, Australia, Section 1, 49–56.

LESLIE, L.M. and R.K. SMITH[4]. A numerical study of katabatic winds and their effect on pollutant dispersal in urban areas. Proceedings, Fifth Australasian Conference on Hydraulics and Fluid Mechanics, 9–13 December 1974, University of Canterbury, Christchurch, New Zealand, Vol. II, 553–560.

McAVANEY, B.J. Southern hemisphere forecast experiments with a one-level spectral model. Abstracts, IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, GARP–II–3.

McAVANEY, B.J. Tropical east-west circulations in a global spectral model simulation. GARP Atlantic Tropical Experiment, Proceedings of the International Conference on the Energetics of the Tropical Atmosphere, 14–21 September 1977, Tashkent, 371–382.

McAVANEY, B.J. Preliminary results of numerical weather prediction experiments over the Winter MONEX region. IAMAP Symposium on the Dynamics of the General Circulation of the Atmosphere II: Tropical Aspects, 17–19 August 1981, Hamburg, Federal Republic of Germany.

McAVANEY, B.J. Tests of the ANMRC tropical analysis scheme using analytic data. Extended Abstracts, Australian Conference on Tropical Meteorology, 24–25 March 1983, Melbourne, Bureau of Meteorology and Roy. Meteor. Soc. Aust. Br., 33–34.

McAVANEY, B.J. The ANMRC tropical analysis system. Fourth Annual Conference on Tropical Cyclone Warning Systems, 2–4 August 1983, Darwin, N.T., Australia, Bureau of Meteorology.

McAVANEY, B.J., W.P. BOURKE and **K.K. PURI.** A simulation of the January global circulation. GARP Report of the JOC Study Conference on Climate Models: Performance, Intercomparison and Sensitivity Studies, 3–7 April 1978, Washington, D.C., 296–317.

McAVANEY, B.J., N.E. DAVIDSON and **J.L. McBRIDE.** The onset of the Australian northwest monsoon during Winter MONEX: Broadscale flow revealed by an objective analysis scheme. Condensed Papers and Meeting Report, International Conference on Early Results of FGGE and Large-Scale Aspects of its Monsoon Experiments, 12–17 January 1981, Tallahassee, Florida, 10.7–10.11.

McBRIDE, J.L. An analysis of diagnostic cloud models. Preprints, Australia — New Zealand GARP Symposium, December 17–19, 1979, Melbourne, Australia, 102–107.

McBRIDE, J.L. Budget analysis of tropical cyclone formation. Abstracts, International Conference on Tropical Cyclones, 25–29 November 1979, Perth, Australia, Roy. Meteor. Soc. Aust. Br., Amer. Meteor. Soc. and Aust. Acad. Sci.

McBRIDE, J.L. Forecasting tropical cyclone genesis: Consideration of patterns of vertical wind shear. Abstracts, International Conference on Tropical Cyclones, 25–29 November 1979, Perth, Australia, Roy. Meteor. Soc. Aust. Br., Amer. Meteor. Soc. and Aust. Acad. Sci.

McBRIDE, J.L. Characteristic space and time scales of the Australian northwest monsoon. Extended Abstracts and Panel Session, International Conference on the Scientific Results of the Monsoon Experiment, 26–30 October 1981, Denpasar, Bali, Indonesia, GARP 5, 50–53.

McBRIDE, J.L. Australian tropical weather systems. Extended Abstracts, Australian Conference on Tropical Meteorology, 24–25 March 1983, Melbourne, Bureau of Meteorology and Roy. Meteor. Soc. Aust. Br., 7–9.

McBRIDE, J.L. Recent research on the southern hemisphere summer monsoon. Preprints, First International Conference on Southern Hemisphere Meteorology, July 31 — August 6, 1983, Sao Jose Dos Campos, Brazil, Amer. Meteor. Soc., 266–269.

McBRIDE, J.L. and T.D. KEENAN[6]. Climatology of tropoical cyclone genesis in the Australian region. Preprints and Abstracts, Symposium on Typhoons, 6–11 October 1980, Shanghai, China, ESCAP/WMO, 20–29.

McGREGOR, J.L. The interaction of cumulus convection with large scale atmospheric motions. Second Australasian Conference on Heat and Mass Transfer, 16–18 February 1979, University of Sydney, Australia, 129–136.

McGREGOR, J.L. A cyclone track prediction method using a primitive equation model. Abstracts, International Conference on Tropical Cyclones 25–29 November 1979, Perth, Australia, Roy. Meteor. Soc. Aust. Br., Amer. Meteor. Soc., and Aust. Acad. Sci.

MILLS, G.A. A limited area analysis/forecast cycling experiment using FGGE data sets. Preprints, Australia-New Zealand GARP Symposium, December 17–19, 1979, Melbourne, Australia, 55–58.

MILLS, G.A. A limited area objective analysis/prognosis experiment using FGGE data in the Australian region. Condensed Papers and Meeting Report, International Conference on Early Results of FGGE and Large Scale Aspects of its Monsoon Experiments, 12–17 January 1981, Tallahassee, Florida, ICSU/WMO, 2.37–2.43.

MIYAKODA[21], K., T. GORDON[21], R. CAVERLY[21], W. STERN[21], J. SIRUTIS[21] and **W. BOURKE**. Simulation of a blocking event in January 1977. Proceedings of the Fifth Annual Climate Diagnostics Workshop, October 22–24, 1980, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, Washington, US Dept. Commerce, NOAA, 331–340.

MIYAKODA[21], K., J. PLOSHAY[21], W. STERN[21], and **K. PURI**. Various four-dimensional analysis methods. Condensed Papers and Meeting Report, International Conference on Early Results of FGGE and Large Scale Aspects of its Monsoon Experiments, 12–17 January 1981, Tallahassee, Florida, ICSU/WMO, 2.32–2.36.

MIYAKODA[21], K., L. UMSCHIED[21], T. TERPSTRA[21], J. PLOSHAY[21], J. SIRUTIS[21], **W. BOURKE**, C.T. JOBSON[21], W. STERN[21], and W. DAVIS[21]. FGGE four dimensional analysis system at GFDL. Condensed Papers and Meeting Report, International Conference on Early Results of FGGE and Large Scale Aspects of its Monsoon Experiments, 12–17 January 1981, Tallahassee, Florida, ICSU/WMO, 1.50–1.58.

NICHOLLS, N. A comparison with earlier estimates of southern hemisphere available potential and kinetic energy estimate from 1979 data. Preprints, Australia-New Zealand GARP Symposium, December 17–19, 1979, Melbourne, Australia, 112.

NICHOLLS, N. Air-sea interaction and long-range weather prediction. Meeting of australian Physical Oceanographers, March 2–5, 1981, CSIRO Cronulla, CSIRO Division of Fisheries and Oceanography, 23.

NICHOLLS, N. Long range weather prediction: value, status and prospects. Proceedings, Farmers and the Weatherman, September 1982, University of Sydney, Aust. Inst. Ag. Sci. Occasional Publication No. 1 (B.G. Sutton, E.A. Fitzpatrick and D.R. De Kantzow, eds.), 81–91.

NICHOLLS, N. Prospects for empirical long-range weather prediction. Proceedings of the WMO–CAS/JSC Expert Study Meeting on Long-Range Forecasting, 1–4 December 1982, Princeton, WMO Programme on Weather Prediction Research (PWPR), Long Range Forecasting Research Pub. Ser. No. 1, 154–166.

NICHOLLS, N. Predicting the onset of the north Australian wet season. Extended Abstracts, Australian Conference on Tropical Meteorology, 24–25 March 1983, Melbourne, Bureau of Meteorology and Roy. Meteor. Soc. Aust. Br., 13–15.

NICHOLLS, N. Statistical climate prediction: the state of the art. II International Meeting on Statistical Climatology, September 26–30, 1983, Lisbon, Portugal, WMO, US NSF and US Office of Naval Res., 13.1.1–7.

NICHOLLS, N. The relevance of the Southern Oscillation to the Australian-Indonesia region. Abstracts, AMSTAC Colloquium on the Southern Oscillation, 27–28 July 1983, Canberra.

NICHOLLS, N., and F. WOODCOCK[6]. Verification of an empirical long-range weather forecasting method. Symposium on Probabilistic and Statistical Methods in Weather Forecasting, 8–12 September 1980, Nice, France, WMO.

PURI, K.K. Normal mode initialization in the ANMRC data assimilation scheme. Proceedings of the (fourteenth) Standstead Seminar, 15–18 July 1981, Bishops University, Quebec, Canada, Dept. Meteorol., McGill University.

PURI, K.K. The relationship between convective adjustment, Hadley circulation and normal modes in the ANMRC spectral model. Extended Abstracts, Australian Conference on Tropical Meteorology, 24–25 March 1983, Melbourne, Bureau of Meteorology and Roy. Meteor. Soc. Aust. Br., 24–25.

PURI, K.K. The impact of FGGE observing systems in the southern hemisphere. FGGE Workshop, 9–20 July 1984, National Academy of Sciences Study Center, Woods Hole, Mass.

PURI, K.K.N. and **W.P. BOURKE.** Implications of horizontal resolution in spectral model integrations. Abstracts, IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, GARP–II–2.

PURI, K.K.N. and R.W. DALEY[9]. Application of normal mode analysis to assimilation of data by numerical models. Preprints, Australia-New Zealand GARP Symposium, December 17–19, 1979, Melbourne, Australia, 42–43.

PURI, K., W. BOURKE and **R. SEAMAN.** Assimilation, analysis and data impact in the southern hemisphere summer. Preprints, First International Conference on Southern Hemisphere Meteorology, July 31–August 6, 1983, Sao Jose Dos Campos, Brazil, Amer. Meteor. Soc., 191–194.

SEAMAN, R.S. Use of satellite data for numerical weather prediction in the southern hemisphere. Proceedings of the Symposium on Meteorological Observations from Space: Their Contribution to the First GARP Global Experiment, 8–10 June 1976, Philadelphia, Penna. USA, COSPAR, 397–403.

SEAMAN, R.S. Objective analysis accuracies of statistical interpolation and successive correction schemes. Preprints, Sixth Conference on Numerical Weather Prediction, 6–9 June 1983, Omaha, Nebraska, Amer. Meteor. Soc., 141–148.

SEAMAN, R.S. Absolute and differential accuracy achievable with specified observational network characteristics. Preprints, Fifth Conferrence on Probability and Statistics in Atmospheric Sciences, 15–18 November 1977, Las Vegas, Nevada, Amer. Meteor. Soc., 85–90.

SEAMAN, R.S. and **L.M. LESLIE**. Numerical analysis and prognosis of fronts. Conference Handbook, Two Day Workshop on Fronts, May 26–27, 1977, Bureau of Meteorology, Melbourne, Roy. Meteor. Soc. Aust. Br., 9.

SIMPSON, R.W. and **W.K. DOWNEY**. The effect of a warm mid latitude sea surface temperature anomaly on a numerical simulation of the general circulation of the southern hemisphere. Abstracts, IAMAP/IAPSO Combined First Special Assemblies, January 1974, Melbourne, AS–III–4.

STRETEN, N.A. Some aspects of the satellite observation of frontal cloud cover over the southern hemisphere. Conference Handbook. Two Day Workshop on Fronts, May 26–27, 1977, Bureau of Meteorology, Melbourne, Roy. Meteor. Soc. Aust. Br., 3.

STRETEN, N.A. An outline of some current meteorological observational studies at ANMRC using sea surface temperature (SST) data. Abstracts, Meeting of Australian Physical Oceanographers, 30–31 August 1979, CSIRO Cronulla, CSIRO Division of Fisheries and Oceanography, 22.

STRETEN, N.A. Southern hemisphere sea surface temperature variability and apparent associations with Australian rainfall. Meeting of Australian Physical Oceanographers, March 2–5, 1981, CSIRO Cronulla, CSIRO Division of Fisheries and Oceanography, 22.

STRETEN, N.A. A prospect of Antarctic meteorology — the Australian experience. Preprints, Antarctica: Weather and Climate, 11–13 May 1981, University of Melbourne, Parkville, Vic., Aust., Roy. Meteor. Soc. Aust. Br., compiled by N.W. Young.

STRETEN, N.A. High latitude climates of the Pacific — past, present and future. Abstracts, XV Pacific Science Association Congress, 1–11 February 1983, University of Otago, Dunedin, NZ, Vol., 2, 228.

TROUP[2], A.J. and **N.A. STRETEN**. A study of satellite observed vortices in the southern hemisphere. Proceedings, International Conference on Weather Modification, September 6–11, 1971, Canberra, Australia, Aust. Acad. Sci. and Amer. Meteor. Soc., 306.

TUCKER, G.B. The role of dynamical models of the atmosphere in pollution problems. Proceedings, International Clean Air Conference, May 15–18, 1972, Melbourne, Australia, Clean Air Soc. Aust. and New Zealand, 5–11.

WILLSON, M.A.G. Statistical-dynamical modelling of climate. First Australasian Conference on Heat and Mass Transfer, May 23, 24, 25, Monash University, Melbourne, Australia, Section 1, 1–8.

CMRC Internal Scientific Reports

No. 1 A proposed time-dependant time averaged model. G.B. Tucker, 1969.

No. 2 Observations necessary for the study of air-land surface interactions. G.B. Tucker, 1970.

No. 3 Operational numerical experiments in hemispheric analysis and prognosis. D.J. Gauntlett, R.S. Seaman and N.A. Streten, 1970.

No. 4 High latitude transient eddies as a source of stratospheric moisture. G.B. Tucker, 1970.

No. 5 A preliminary investigation into the use of satellite cloud pictures to estimate average relative humidity below 500mb in the Australian region. J.L. McBride, 1971.

No. 6 Estimation of diurnal height variations of constant pressure surfaces. M.E. Voice, 1971.

No. 7 Initialisation experiments in the southern hemisphere. D.J. Gauntlett, 1971.

No. 8 Comparisons between explicit and semi-implicit time differencing schemes for simple atmospheric models. R.C. Bell, 1971.

No. 9 A study of satellite observed cloud vortices in the southern hemisphere. Part I — Vortices related to conventional data. N.A. Streten and A.J. Troup[2], 1971.

No. 10 A study of satellite observed cloud vortices in the southern hemisphere. Part II — Synoptic climatology and hemispheric circulation aspects. N.A. Streten and A.J. Troup[2], 1971.

No. 11 A diagnostic experiment on dynamic adjustment of surface pressure. R.S. Seaman, 1971.

No. 12 Southern hemispheric barotropic prediction incorporating terrain effects. M.E. Voice, 1971.

No. 13 Aspects of Late Quaternary climate in tropical Australasia. P.J. Webster and N.A. Streten, 1972.

No. 14 A proposed semi-implicit time integration scheme for the N30/six level primitive equation model. D.J. Gauntlett, 1971.

No. 15 Analyses of surface pressure and surface temperature. M.E. Voice, 1972.

No. 16 The CMRC optimised filtered baroclinic model — Evaluation of the Australian region version under parallel real time conditions. P.F. Noar and J.R. Young, 1972.

No. 17 Statistical dynamical modelling of the atmosphere. M.A.G. Willson, 1973.

No. 18 The atmospheric circulation of the extratropical southern hemisphere. A selected bibliography. N.A. Streten and F. Taubman, 1973.

No. 19 Some satellite observations of oceanic and continental contrasts in equatorial cloud features. N.A. Streten and W.R. Kellas, 1973.

No. 20 An Australian region P.E. numerical weather prediction model. D.K. Purnell, 1973.

ANMRC Technical Reports

No. 1 Statistics on the simultaneous variation of wind in time and space — Australian region, 20 000 and 40 000 ft. R.S. Seaman and I.M. Draudins, 1975.

No. 2 Errors in VTPR temperatures over the southern hemisphere R. Dingle, 1977.

No. 3 An objective analysis scheme for the tropics. N. Davidson, 1979.

No. 4 Evaluation of MSL prognoses from the Australian region primitive equations model — a 30 day survey. W.K. Downey, J.L. McGregor and N. Nicholls, 1980.

No. 5 Directional dependence of spatial variability for winds in the Australian region. R.S. Seaman and F.J. Gauntlett, 1980.

No. 6 Spatial correlations of geopotential and temperature in the Australian region. R.S. Seaman, 1981.

No. 7 Statistics on the vertical variation of geopotential, temperature and wind, Australian region, 1000 to 50mb. R.S. Seaman, 1982.

Miscellaneous Publications, Reports and Newsletters

CLARKE, R.H. (1978). The future of weather forecasting in Australia. A lecture delivered to the Bureau of Meteorology, 3 November 1977, ANMRC, 44 pp.

GARRETT, D.R. (1973). A comprehensive verification system. CMRC, 115 pp.

GAUNTLETT, D.J. (1975). The application of numerical models to problems of meteorological analysis and prognosis over the southern hemisphere. Bureau of Meteorology, Meteorological Study No. 28, 181 pp.

GAUNTLETT, D.J., D. BURRIDGE[26] and K. ARPE[26] (1977). Comparative integrations with the ECMWF global forecasting model. I. The N24 experiment. ECMWF Internal Report No. 6, 86 pp.

HUGHES, R.L. (1979). A highly simplified El Nino model. **Ocean Modelling** (Newsletter), No. 22.

HUGHES, R.L. (1979). A possible explanation of the dilemma concerning the width of equatorial response. **Ocean Modelling** (Newsletter), No. 27.

HUGHES, R.L. (1982). The energetics of merging anticyclonic eddies. **Ocean Modelling** (Newsletter), No. 42.

HUGHES, R.L. (1982). Aspects of equatorial mixed layer dynamics. **Tropical Ocean Atmosphere Newsletter**, No. 9.

HUGHES, R.L. (1982). On bottom friction in an equatorial shallow basin. **Oceanographic Tropicale.**

HUGHES, R.L. (1982). The concept of "stagnation vorticity" and a new geophysical wave. **Ocean Modelling** (Newsletter), No. 47.

KININMONTH, W.R. A description of the CMRC primitive equation numerical weather prediction model. CMRC, 50 pp., figs.

McAVANEY, B.J. (1981). Short range numerical weather prediction experiments over the Winter MONEX region. Department of Meteorology. Florida State University, 40 pp., figs.

McAVANEY, B.J. (1982). Some general notes on spherical harmonics. Documentation for the Community Climate Model (CCM), Version Ø, Climate Section, National Center for Atmospheric Research, Boulder, Co. (W.M. Washington, ed.), I.2.

McAVANEY, B. (1982). Notes on individual subroutines. Documentation for the Community Climate Model (CCM). Version Ø, Climate Section, National Center for Atmospheric Research, Boulder, Co. (W.M. Washington, ed.), III.3.

MILLS, G.A., L.M. LESLIE, J.L. McGREGOR and **G.A.M. KELLY**. A high resolution numerical analysis/forecast system for short term prediction over the North American region. A collaborative research project involving the National Environmental Satellite Service (NOAA) and the Australian Numerical Meteorology Research Centre, 22 pp., figs., appendices.

NICHOLLS, N. (1981). Long-range weather prediction for Indonesia. WMO/UNDP Project INS/78/042 Working Paper 14.

NICHOLLS, N. (1984). El Nino Southern Oscillation and north Australian sea surface temperature. **Tropical Ocean Atmosphere Newsletter** No. 24: 11–12.

PURI, K. (1982). Model subroutine definitions for CCM. Documentation for the Community Climate Model (CCM), Version Ø, Climate Section. National Center for Atmospheric Research, Boulder, Co. (W.M. Washington, ed.), III.1.

PURI, K. (1982). Field dependencies and control for CCM. Documentation for the Community Climate Model (CCM), Version Ø, Climate Section, National Center for Atmospheric Research, Boulder, Co. (W.M. Washington, ed.), III.2.

PURI, K. and W.F. STERN[21] (1984). Experiments to reduce noise and improve data acceptance in a continuous data assimilation system. **Research Activities in Atmospheric and Oceanic Modelling,** (in press).

SEAMAN, R.S. (1979). Data assimilation experiments. ECMWF Technical Report No. 12, 65 pp.

VOICE, M.E. (1983). Drought and the physics of the atmosphere. **Meteorol. Aust.,** Roy. Meteor. Soc., Aust. Branch.

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Appendix II

Professional Staff

T.P. ACKERMAN, MSc PhD, 1976–1979

After completing his PhD at the University of Washington, Seattle, USA, Tom joined the Centre in March 1976. He worked in the Climate Research Group primarily on problems of atmospheric chemistry and radiation. Tom returned to the USA in June 1979.

M.E. ADAMS, BSc, 1969–1971

Mary, a computer programmer with the Bureau of Meteorology, was attached to the CMRC's staff on its establishment in April 1969, and provided assistance with projects on the early development of the hemispheric primitive equation model. She resigned from the Centre in May 1971.

D.L.T. ANDERSON, BSc PhD, 1969–1973

David was appointed to the CMRC in mid September 1969 while still in the UK, coming to Melbourne in December 1969 on a three year Post Doctoral Fellowship. He worked in the General Circulation Group developing a nine-level stereographic model (based on a GFDL version) for southern hemisphere circulation studies.

He returned to the UK in March 1973 to take up a position in ocean modelling with the University of Cambridge. In February 1979 David returned as a visiting scientist for approximately six months, during which he worked on a number of projects, one being to clarify the influence of high frequency forcing in a coupled atmosphere ocean model.

In David's words:

I joined the CMRC within months of its inception. This was for me my first exposure to meteorology, and looking back it was an exciting time as forecast and general circulation models were developed and improved, as the spectral model emerged, showed promise and became a real alternative to grid point models.

To have research scientists and experienced meteorologists working side by side seemed so natural that when I subsequently left the CMRC I was surprised this was not the rule. This mix undoubtedly contributed to the success and fame of the CMRC in numerical weather prediction. More recently with the development of several efficient general circulation models based on the spectral technique its fame has grown. While the Centre is perhaps best known for its spectral work, it has also achieved recognition in other fields: climate, mesoscale processes, and fine mesh modelling. It is to me sad that it should be closed at a time when it was developing an oceanographic effort and moving towards the design of a coupled atmosphere-ocean model, so necessary if climate variability is to be studied properly.

Having first worked at the CMRC and later returned as a visitor to the ANMRC, I have on both occasions found the Centre a delightful place in which to work: the staff were friendly, the work varied and of high quality. It is with great regret that I realise it will not be possible to arrange a future visit to what I consider one of the best groups in atmospheric modelling in the world.

A.A. BARKER, MSc PhD, 1971–1974

Tony joined the Centre in March 1971 following the completion of post doctoral research in plasma physics at the University of Florida, USA. During his three years with the Centre he investigated the radiative properties of clouds and convective parameterization formulations using an 18–level general circulation model.

He returned to his home state of South Australia in late March 1974.

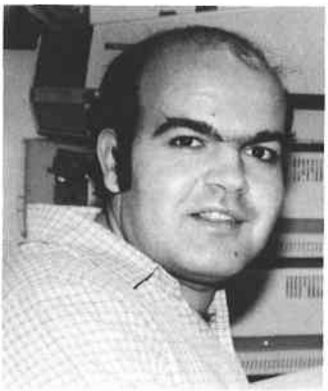
J.R. BLAKE, BSc PhD, 1969–1971

Roger spent from June 1969 to April 1971 with the Centre coming from the University of Alaska. He worked on the mathematical treatment of cyclogenesis and frontal instability in the southern hemisphere. Roger resigned from CSIRO to take up a position with the Royal Melbourne Institute of Technology.

N.G. BLENCOWE, MSc, 1969

Noel was a foundation Meteorologist with the CMRC in April 1969, assisting with the early development of the hemispheric and Australian region forecasting models. Noel resigned late in 1969.

P. BOCA, BA, 1980+



Pat joined the ANMRC in mid 1980 as a Computer Systems Officer. In his four years with the Centre he has provided considerable support to the Tropical Research Group in the development of the operational tropical analysis system, and in enhancements of data handling systems.

W.P. BOURKE, MSc PhD, 1969+

In anticipation of the establishment of the CMRC, Bill was employed temporarily at the CSIRO Division of Meteorological Physics (as it was called then) from January 1969. He was transferred to the Centre upon its inception. As mentioned else where in this report Bill is known for his work on developing spectral models of the atmosphere. Early developmental work on spectral transform methods was carried out while he was at McGill University and the Dynamic Prediction Unit of the Canadian Meteorological Service (Montreal, Canada) for ten months in 1970–71.

With the continued development of this model a Spectral Modelling Group was established under Bill's leadership, continuing until early in 1978 when it was merged with the existing Weather Research Group. On further reorganization in 1980, Bill became leader of the scientists undertaking the large scale component of weather research, known as the Medium Range Prediction Group. From April 1983 he has been Acting Officer-in-Charge of the Centre.

Other overseas visits Bill made were to Denmark, the UK, the USA and Canada for a six week period in August/September 1974; to GFDL, Princeton for 12 months from May 1977; to Norway and the UK for three weeks in June/July 1980; and for 12 months from August 1981 to work as a Visiting Scientist at the ECMWF.

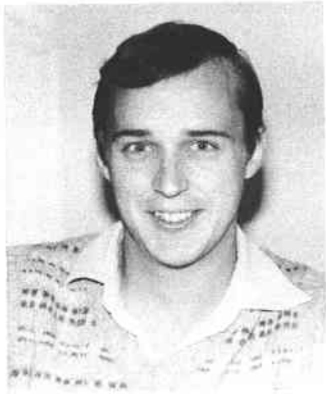
Bill's personal comments follow:

I came to meteorology in an appropriately unpredictable fashion. A chance attendance at a seminar as a sporting respite from the rigours of thesis preparation on alpha particle scattering provided the necessary stimulus. The seminar still clearly remembered was as a bolt from the blue; it was presented with a conviction and excitement that identified for me an area of relevance for mathematical physics I had not previously appreciated. I am especially indebted to Dr C.H.B. Priestley for that presentation by Lake Burley Griffin in 1968.

Over the past 15 years my colleagues in CMRC/ANMRC have validated for me the substance of that first seminar on the Global Atmospheric Research Programme. It has been a great experience to work and research at the Centre and to have had the opportunity to pursue interests further with overseas colleagues on several occasions.

Along with many others I argued the merits of the Centre at innumerable reviews. In some sense we won the arguments with those with whom we had dialogue. The imperative of rationalization however, had different boundary conditions and forcing; this only reaffirms that predictability is a difficult problem.

G.R. BUDIN, BSc, 1984+



Garry commenced duty with the ANMRC in January 1984, having completed the Meteorology Training Course with the Bureau. Previously he had worked with the Centre as a vacation student in 1980/81. He has been working in the Diagnostic Studies Group on analysis of the interannual variability of the 10 year simulation by the two-level climate model.

R.H. CLARKE, BA MSc DSc, 1974–1978

Reg succeeded Brian Tucker as Officer-in-Charge of the ANMRC in November 1974. Formerly he had been a Research Scientist with CSIRO Division at Atmospheric Physics from 1957, and prior to that a Meteorologist with the Bureau from October 1940. He conducted research into problems associated with the atmospheric boundary layer, particularly the nature of sea breezes, and contributed substantially to the Wangara and Koorin expeditions.

Reg continued some of his boundary layer research while directing the Centre's activities. Comments on his time as Officer-in-Charge are included in an earlier chapter of this report. From August 1975 Reg spent three months visiting various research institutes in the USA, Canada, UK, France, Japan and South Africa. Since retiring in January 1978 he has been a Senior Research Associate with the Meteorology Department of the University of Melbourne, held the position of chairman of the Australian Branch of the Royal Meteorology Society, and led the 'morning glory' expedition to the Gulf of Carpentaria in late 1979. Reg was awarded a DSc from the University of Melbourne in 1982 for his work on boundary layer measurement, numerical modelling of mesoscale phenomena (in particular the sea breeze), and the parameterization of boundary layer components in general circulation modelling.

N.E. DAVIDSON, BSc, 1979+

Noel took up temporary duty for four months with the ANMRC in early 1977, from the Victorian Regional Forecasting Centre in Melbourne. He worked in the field of temperature retrieval from satellite data. In late 1979 Noel was promoted to a permanent Meteorologist position with the Centre. His major contribution has been the development of an objective tropical analysis scheme. He shared the first Priestley Medal to be awarded (1981–82) with B.J. McAvaney for their paper in the Australian Meteorological Magazine describing this system. He has also contributed to the Centre's research into the dynamics of the Australian monsoon.

R. DEL BEATO, BSc, 1980

Romano, a Meteorologist in the Research and Development Branch of the Bureau joined the Centre in a temporary capacity, from February to June 1980, in the absence of W. Downey. He continued his quantitative precipitation forecasting study using satellite imagery and numerical thickness pattern prognoses.

R.E. DINGLE, BSc PhD, 1974-1977

Rod commenced duty with the Centre in May 1974 coming from the Research and Development Branch of the Bureau. He assisted in the assessment of operational trials of the spectral model, and continued his work on a surface temperature prediction scheme. Rod transferred to the South Australian Regional Forecasting Centre of the Bureau in Adelaide in October 1977.

W.K. DOWNEY, FRMIT PhD, 1972-1982

Bill returned to Australia in October 1972 from the University of Wisconsin (UW) to join the CMRC. He carried out one of the earlier sea surface temperature anomaly experiments using a general circulation model of the atmosphere. In consultation with UW he developed a numerical budget scheme to assess the roles of various physical and dynamical processes in the evolution of synoptic systems, both in actual and model generated situations.

Bill returned to UW in May 1974 for seven weeks, and again for five months in 1980 as an Honorary Fellow.

After several months in the Director's Office (Bureau of Meteorology) in Canberra in late 1981, Bill was attached to Ansett Airlines under the Public Service Board Interchange Program. He also spent five months with the Department of Aviation before returning to the Research and Development Branch of the Bureau.

Bill adds the following:

ANMRC — A TEST OF 'ENDURANCE'

In December of 1914, Ernest Shackleton's Trans Antarctic Expedition sailed into Antarctic waters aboard the 'Endurance'. On December 9, whilst still north of the Antarctic Circle the 'Endurance' found herself flanked by two giant icebergs. Only by recourse to an ice anchor, capstan and the strength of her crew did she avoid being crushed by the mountains of ice on either side.

On January 15, 1915, now only a few miles off the Antarctic coast and in heavy pack ice, the 'Endurance' tried to move between two huge bergs into what looked like open sea beyond. However, within a few hours a gale force wind from the ENE forced the 'Endurance' to take refuge on the lee side of one of the bergs. On January 18 when the gale subsided slightly, the 'Endurance' was stuck fast in the vast pack ice of the Weddell Sea. After drifting in the pack for many months, the enormous pressures of the ice finally (October 27) crushed the ship as if it were a matchbox. On November 21 the members of the expedition watched as bow first, 'Endurance' sank through the ice some 500 miles from where she was first beset. Two months earlier one of the party (Worsley) had written: "All hands are standing by, but to our relief just as it appears she can stand no more, the huge floe weighing possibly a million tons or more yields to our little ship by cracking across, ¼ of a mile, and so relieves the pressure. The behaviour of our ship in the ice has been magnificent. Undoubtedly she is the finest little wooden vessel ever built."

Like the 'Endurance' the ANMRC was a vehicle by which scientists were attempting to explore and understand the mysteries of the environment in which we live. Unfortunately she always found herself in a political environment characterised by stormy seas and monolithic icebergs. However, just as Shackleton's group went on to survive and take a place in the history of exploration, so too will many of those who sailed aboard the ANMRC. As we watch her final demise it seems appropriate to say "She was a gallant little ship".

I.M. DRAUDINS, BSc, 1971–1975

Ilmars commenced duty with the CMRC in late 1971 as a Programmer, working with the Weather Research Group. In August 1975 he resigned from the Centre to take up a position in private enterprise with the National Cash Register Company, and later moved to Control Data of Australia where he is now Institute Manager, Melbourne.

G.K. EMBERY, BSc, 1979+

Gerry, a Computer Systems Officer, joined the Centre early in 1979, from the Bureau of Meteorology and has been attached to the Medium Range Prediction Group. He has played a major role in the programming development of the ANMRC four dimensional assimilation system scheduled for operational use in mid 1984. Gerry was a 'guest worker' with CSIRO Division of Computing Research in Canberra for three months from December 1980, involved in software development on various computer graphics packages.

P.G. ENGLAND, BSc, 1970–1977

Peter transferred to a Programmer position with the CMRC in March 1970. His earlier years with the Centre were involved in the development of numerical weather analysis and pre-analysis routines suitable for operational use by the Bureau. Later he was attached to the Climate Research Group to assist with the development of general circulation models on CSIRO's CYBER 76 computer. Peter resigned from the Centre to take up a position with the Bendigo College of Advanced Education in April 1977.

R.L. FALCONER (late), BSc, 1969

Bob joined the Centre from the Bureau on its establishment in April 1969. He was largely involved with the operational implementation of the first analysis-prognosis system for the Bureau, and subsequently its maintenance and updating. Late in 1969 he returned to the Bureau to lead the Operational Development Group (now ODSS). The interface of much of the ANMRC NWP modelling research to operational application involved a substantial contribution from Bob. His death in 1978 was a significant loss to meteorology as well as to those who knew him in CMRC and in the Bureau.

C.B. FANDRY, BSc PhD, 1980–1983

Chris joined the Centre in February 1980 initially for a period of 18 months funded by the Victorian Institute of Marine Sciences (VIMS). During this time he was successful in securing several AMSTAC grants to support his development of a numerical model of Bass Strait. In July 1981 Chris was appointed to a fixed term Research Scientist position at ANMRC and continued to expand his work on Bass Strait as well as complete research on a number of other topics mentioned below in his personal comments.

Chris also made a number of short overseas visits: To Oregon State University, NCAR and GFDL in the USA in mid 1982; again to the USA in December 1982; and to attend several symposia in Europe in August/September 1983.

In November 1983 he took up a permanent position with CSIRO Division of Oceanography in Hobart, Tasmania. His comments follow:

In many respects my background as a geophysical fluid dynamicist/physical oceanographer would normally have precluded me from obtaining a position at ANMRC. However, as a result of an initiative proposed by D.J. Gauntlett (Officer-in-Charge), my services were requested to develop a numerical hydrodynamical model of Bass Strait. This project has been extremely successful in providing new information about the characteristics of tides and currents in Bass Strait. This diversification of ANMRC's research program extended its reputation both nationally and internationally. As a result, important collaborative projects, for example with the Victorian Institute of Marine Sciences and R.K. Steedman and Associates to study Bass Strait, the North-West Shelf, numerical ocean wave prediction models, and tropical cyclone induced surges along the west coast of Australia were completed.

Together with these projects, other studies of a more fundamental nature with both oceanographic and meteorological applications were undertaken. These studies included theoretical modelling of the ocean mixed-layer, stationary Rossby waves in the atmosphere, blocking and the west coast heat trough. It is important to point out that these studies were *motivated by discussions with meteorologists both at ANMRC and the Bureau of Meteorology and would not have been successful without their input.*

The practical nature of the work carried out by the meteorologists at ANMRC was of great benefit, as it provided me with a continual source of interesting, challenging problems. Unfortunately, as a result of the decision to close the Centre, many of these problems were only barely considered or remain unsolved.

The blending of the theoretically and the more practically orientated scientists, I believe is essential to the successful operation of a research establishment, such as ANMRC.

B.W. FORGAN, BSc PhD, 1980-1984

Bruce joined ANMRC as a Meteorologist in early 1980 coming from the Ionospheric Prediction Service in Western Australia. His main areas of work have been in developing a radiation scheme for the extended range prediction spectral model, and investigation of a number of approaches to improve temperature data retrieval from meteorological satellites. He maintained a substantial interest in other areas of research associated with solar radiation.

In mid 1983 Bruce visited a number of research institutes in the USA, and attended several AMS conferences.

Bruce was promoted in March 1984 to Officer-in-Charge of the Bureau's Cape Grim Baseline Air Pollution Station in Tasmania.

In his words:

A JAUNDICED VIEW

It would be a very lean contribution, from one such as I, to comment on the history of the ANMRC or its evolution. I am only a young member of the ANMRC and therefore will leave the valedictory statements to those more informed. Rather, my comments consist of a personal impression of the ANMRC, most certainly a jaundiced one.

I joined the ANMRC after a misconceived haji into the outback posing as a solar physicist. My fresh ivory tower views on research were dampened during this misguided pilgrimage and the opportunity to work at the ANMRC, in a field professing to be something related to my studies, kindled my enthusiasm. During my time at the ANMRC, my appreciation of its role waxed and my basic impression of its directions and its people crystalized. I do not read poetry often, however some stanzas remain. One of these gives life to my view of the ANMRC:

"Two roads diverged in a wood, and I —

I took the one less travelled by."

All the roads are science in its many branches, all leading off in the quest for knowledge. Those who discover different places are the 'pure' scientists; those who travel the well worn path are the operational scientists. The ANMRC is equivalent to the construction company, because once a place is discovered, it has to be opened to the ultimate users. The ANMRC is the interface between new directions and their implementation.

Like all road builders, there are the surveyors and the road gang. Surveyors get the opportunity to travel up the little paths attempting to find appropriate routes. The road gang cuts down the problems in the algorithms once the path has been laid, and widens the application *of the science. Road construction crews by their very nature have to work as a team, and the ANMRC has had some good ones. I have been fortunate enough to work in at least two of them, for the majority in the capacity as an algorithm jockey. The only regret I have is that some of the other gangs, while ultimately heading in the same direction, have failed to use community tools. However, competition between groups has been keen and it is a pity we have all been retrenched.*

As a final note I should say something about the two elements of the ANMRC team. Surveyors are recruited from the world outside; gangers on the other hand, can work their way up and eventually be recognised as potential surveyors. By that time however, they have usually side-stepped into administration. By my recruitment route I consider myself part of the road gang, but with a tendency to wander off on occasions, sniffing at flowers, or trying to look over the hill into the next valley. A succession of road construction managers has generally been tolerant of this out-of-character activity. Maybe they can sense the routineness of repairing potholes or putting in new water fountains, and that has made all the difference. (Apologies to Robert Frost.)

D.R. GARRETT, MSc, 1972–1974

Don joined the CMRC in January 1972 as a Meteorologist to assist with evaluation of real time operational tests of the Centre's forecasting models. Don developed a comprehensive verification-feedback system which was subsequently implemented operationally by the Bureau. He was promoted to a position in the Bureau in March 1974.

D.J. GAUNTLETT, BSc PhD, 1969–1983

Doug was attached to the CMRC on its formation in April 1969 from the Bureau (Head Office). At this time he was overseas at GFDL Princeton Univerisity developing a southern hemisphere primitive equation forecasting model based on a very successful GFDL formulation. Much of his work at the Centre involved the subsequent development of this model, particularly the Australian region version. His PhD awarded by the University of Melbourne in 1974 was based on the earlier stages of this research.

Doug was leader of the Weather Research Group until early 1978. In March 1980 on the dissection of this Group, he assumed leadership of the Regional and Mesoscale Prediction Group. He acted as Officer-in-Charge from March 1973 to November 1974, and in 1975 joined the CSIRO as a Research Scientist with the Centre. He was appointed Officer-in-Charge in early 1978.

In March/April 1972 Doug visited a number of scientific institutions in the USSR, Europe and North America. He spent 12 months at the ECMWF in the UK in 1976–77, involved with the development and evaluation of a global forecasting model. Further short term visits were made in mid 1981 to the USA, UK and West Germany, and in April 1982 to the UK.

Doug was appointed to the new position of Deputy Director (Research and Systems) with the Bureau in April 1983.

F.J. GAUNTLETT (nee Taubman) BSc, 1970+

Frances joined CMRC in December 1970 from the University of New England, NSW, as its Scientific Services Officer. She has been responsible for maintaining the Centre's library, compiling and editing annual and internal reports, and assisting the Officer-in-Charge with the preparation of technical reports or submissions as required. At times she has also collaborated on several research projects of the Weather Research Group.

S.E. GIGLIUTO, BSc, 1983+

Sam joined the ANMRC as a Computer Systems Officer in July 1983, coming from LaTrobe University. He has been attached to the Regional and Mesoscale Prediction Group and has been closely associated with the development of the Bureau of Meteorology — Division of Atmospheric Research Hewlett-Packard computer link as well as interfacing the Bureau's local network and CSIRONET.

H.B. GORDON, BSc PhD, 1976+

Hal joined the ANMRC in April 1976 after completing a PhD at the University of Exeter. He has developed a two-level spectral model of the atmosphere which is being used for multi-annual experiments and which is being coupled with an ocean model. In March 1981 Hal ceased duty with CSIRO and took up a Meteorologist (Bureau) position in the Centre.

J.K. GUARINO, BSc, 1983 and 1984

Jenny has been employed on several occasions as a Computer Systems Officer when there has been a temporary vacancy at the Centre. She has supported the Climate Research Group and worked on graphics development.

T.F. HALES, BSc PhD, 1975

Trevor was employed temporarily by the Centre for ten months as an Experimental Officer, prior to commencing further study in the UK. He assisted with developing the six-level semi-implicit Australian region forecasting model, and a concentrated vortex model. He has since completed a PhD in computing science at Oxford and is now a member of the CSIRO Division of Computing Research.

T.L. HART, MSc, 1984+

Terry commenced duty in the Centre in June 1984 coming from the Bureau (Head Office) to work in the Medium Range Prediction Group, in particular on the further development of the radiation scheme for the spectral and regional prediction models.

D.R. HINCKSMAN, BSc, 1969–1977

David was a foundation member of CMRC's programming staff, coming from the Bureau of Meteorology. He worked mainly on the development of the Centre's hemispheric and regional primitive equation models. In late 1969 he visited the Geophysical Fluid Dynamics Laboratory, Princeton, USA, for three months to assist in the adaptation of the GFDL nine-level N40 model to a six-level N30 (primitive equation) model for southern hemisphere forecasting, suitable for running on the Bureau's IBM machines.

From 1970 David was the senior Programmer with the Centre, providing considerable support and advice in this area for the staff. He transferred to a position with the Bureau in June 1977.

D.J. HOUSE, BSc, 1971

Prior to commencing post graduate studies in the UK, Dianne was employed for eight months by CMRC as an Experimental Officer to develop a simplified radiation scheme suitable for use in a general circulation model.

R.L. HUGHES, MEngSc PhD, 1978–1983

Roger completed his PhD in Oceanography at the University of Cambridge and joined the Centre in October 1978, working in the Climate Research Group on tropical oceanic and atmospheric dynamics. He discovered and developed a method for modelling baroclinic flow suited to the seas of south east Asia, and developed a model to explain irregularities in the sea-ice distribution of Antarctica. Roger also designed a simple ocean model suitable for coupling to an atmospheric general circulation model.

In July 1982 Roger joined the Department of Geology and Geophysics at Yale University for an extended visit. He resigned from the Centre in July 1983 to continue his work at Yale, as well as to avoid the continued uncertainty regarding his position upon the eventual closure of the ANMRC.

In Roger's words:

When ANMRC finally closes its doors, it will be the end of a very successful experiment between CSIRO and the Department of Science. Whether the Centre was always on borrowed time or not does not really matter now. The Centre worked smoothly and we worked smoothly in it.

Maybe the future will correct me, but I don't think any of us were truly brilliant scientists. We were all extremely competent at what we did and we enjoyed doing it. We had very good leadership. With numerical weather research demanding team work and more conceptual climate research demanding personal initiative, we had the leadership styles we needed. Yet small a group as we were, we were known widely overseas and with good standing.

Certainly having the combined resources of the Bureau of Meteorology and CSIRO with Melbourne University so close at hand helped us. Sometimes the resources available required a bit of prising but they were vast. I remember, briefly feeling a little despondent about the amount of oceanographic data I had for some project. Little did I know how much unpacked data lay in those notorious brown cardboard boxes which had been used for relocating the Bureau library! With a trippling of library staff, I was soon elated to find all the data I needed. Even though I was on the theoretical rather than applied side of the Centre's activities, I felt the strong support of the Bureau.

While the leadership and resources available to us were important in what we achieved, they cannot explain the cooperative attitude within the Centre, which I think underlay its success. All would agree that as a general rule scientists tend to be intense and moody by nature! The Centre had its share, including myself, of those fitting the stereotype. Yet we got on remarkably well; better than in other organizations in which I have worked. Certainly morning and afternoon teas, with weather charts and plenty of jokes about rival research organizations, cemented us together. However, there is more to it. Besides going about their own work, some of the support staff unwittingly produced this unity. One morning I received a request card with the wording

"I would not appreciate a copy of . . ." The word "not" had been inserted by hand. I was so ashamed I hid the card. The next day I was told who had really inserted the "not". Nevertheless this innocent practical joke had a message for me. Similar incidents seemed to occur whenever anyone started to take their own particular work too seriously. The net result was that we laughed more at ourselves and worked together better. In retrospect I am sure this was what made the Centre different.

When I left the Centre, I was tired and my emotions showed. Everyone who worked there for a year or so must have some feeling of regret at leaving. ANMRC was a successful experiment because it occurred with cooperation between friends. I shall not forget working at the Centre and the friends I had there.

B.G. HUNT, MSc, 1969–1984

Barrie was employed temporarily at the CSIRO Division of Meteorological Physics from mid 1968 in anticipation of the Centre's establishment in April 1969. His early research included investigation of the role of photochemistry in the chemical structure of the upper atmosphere. With over two years prior experience at GFDL in the USA from 1965, Barrie's major contribution has been the development of global numerical models for simulating the general circulation of the atmosphere. These have included the semi-spectral or Fourier model, and its extended version to 100 km; and the stereographic model, for which the original code was developed in collaboration with GFDL. He has used these models for a considerable number of geophysical experiments to probe atmospheric and environmental effects.

Barrie was leader of the General Circulation (later Climate Research) Group from the establishment of the Centre, and has been acting Officer-in-Charge for brief periods on several occasions. He made a short visit to the USA in February 1972, and for three months in mid 1974 he visited research institutes in the USA, UK and Europe. In late 1980 Barrie made a further three month visit to the USA and Europe to assess relative climatic programs in Australia and overseas.

Barrie transferred to the CSIRO Division of Atmospheric Research in July 1984.

D.J. KAROLY, BSc PhD, 1980–1983

David joined the ANMRC in December 1980 on the completion of a PhD at the University of Reading. He was a member of the Climate Research Group until February 1983 when he accepted an appointment with Monash University as a lecturer in the Mathematics Department. During his term with the Centre his work was directed towards understanding the forcing, propagation and structure of planetary waves, as well as their poor representation in numerical models. The latter part of his time was spent developing a climatology for the southern hemisphere based on numerical analyses.

In July/August 1981 he visited the UK and West Germany for five weeks.

His comments follow:

There were two major influences on my work during the two years I was employed at ANMRC as a fixed-term Post Doctoral Research Fellow. The first of these was the use of fixed-term appointments in ANMRC, and possibly in other CSIRO Divisions, as an unofficial probationary or assessment period in deciding the suitability of the appointee for a permanent Research Scientist position. Officially, this does not and cannot happen, but it actually was the dominant factor in my decisions on which research problems I should work. Since this assessment is largely based on the number of publications during the fixed term, I decided to work on small, manageable problems which were likely to lead to quick results and publishable material rather than on major and perhaps more useful problems.

The second major influence on my work was the Review of Atmospheric Sciences in CSIRO and the prior decision to disband ANMRC. At this stage, I realised that the possibilities for joint research between CSIRO and the Bureau of Meteorology might be reduced in the future and that I should take advantage of the unique situation of ANMRC to attack a problem which I felt was major and likely to lead to some useful long term results even if not to something publishable in the short term. I decided to use the southern hemisphere (SH) daily numerical analyses of the Bureau to investigate large scale interannual variability of the SH troposphere and to create a facility for generating real time SH climate diagnostics as an aid for extended range prediction. I spent much of my last year at ANMRC setting up such a SH data diagnostics system.

In October 1982, I decided to accept a continuing lectureship in the Mathematics Department, Monash University, as I felt very uncertain about my job security, with my fixed term position due to end in one year, ANMRC due to disband and no real indication from CSIRO or the Bureau about employment prospects at the end of my fixed term position.

I am very grateful to Bill Bourke for allowing me to continue at ANMRC as a visiting scientist after I started at Monash since this has meant that I can continue working on the SH data and several joint publications are likely in the near future.

G.A.M. KELLY, BSc, 1970+

Graeme joined the CMRC in September 1970 from the Bureau of Meteorology (Head Office). He has led a small group specializing in developing techniques for the retrieval of temperature and moisture profiles from satellite radiance data (in collaboration with W. Smith of NESDIS, University of Wisconsin). This has involved demonstrating their positive impact on both regional and hemispheric forecasting, resulting in their operational use. In 1983 a local read-out and high resolution temperature retrieval facility for operations and research was implemented under Graeme's leadership. Another area of involvement has been in establishing a ten year southern hemisphere climatology based on the Australian operational numerical analyses.

Since early 1983 Graeme has been leader of the Regional and Mesoscale Prediction Group. He spent five weeks at NESS Washington D.C., as well as visiting various other research institutes involved with satellite data retrieval, from April to June 1975. From October 1978 Graeme spent 12 months at the University of Wisconsin to participate in evaluating high resolution sounding data from the TIROS–N satellite in limited area forecasting applications. Currently he is spending 12 months at the ECMWF as a visiting scientific consultant.

D.W. KEENAN, MSc PhD, 1983–1984

Dan commenced duty with the Centre in August 1983 coming from the Bureau's Regional Forecasting Centre in Darwin following on from an earlier career in theoretical astronomy. He has been developing a surface temperature analysis for use in the tropical analysis program to work in conjunction with the analysis of TOVS satellite data.

In September 1984 Dan accepted a Research Scientist appointment with the Defence Research Centre, South Australia.

W.R. KININMONTH, MSc, 1970–1974

Bill joined the Centre as a Meteorologist in September 1970 after a period of study leave from the Bureau at Colorado State University, USA. He developed a cloud model to parameterize convection, and worked on problems associated with improving the physics of the six-level primitive equation forecasting model.

In mid 1973 Bill spent a month overseas to attend a WMO/IAMAP symposium in the UK, and to visit a number of research institutes there and in the USA. After a period of temporary duty with the Research and Development Branch of the Bureau he took up a permanent position there in July 1974.

J.F. LE MARSHALL, BSc PhD, 1975–1979, 1984

John joined the Centre in June 1975 from the Victorian Regional Forecasting Centre of the Bureau. His main area of work was on temperature inversion methods for the retrieval of data from meteorological satellites, and hemispheric analysis for the spectral model.

John was promoted to a position in the Analysis Section, Services Branch of the Bureau which he took up in July 1979. He rejoined the Centre in October 1984.

Comments on his view of ANMRC are included:

It is difficult to write a eulogy for the ANMRC while the body corporate is still exhibiting an impressive vitality.

While not wishing to talk in detail of my own work in the remote sensing, climatology and analysis and prognosis areas, I feel it is important that some general comments be made about this felicitous combination of subjects which were studied at the ANMRC. The study of these *fields was an early recognition of the holistic nature of the overall observational, analysis and prognostic problem, and this problem itself addresses in real terms, the uncertainties of the science at large. The ANMRC from its earliest days devoted itself to a pragmatic solution of the problem, ever aware of the operational requirements of the Bureau. This endeavour is reflected in no small part by the high quality of forecast advice given by the Bureau to the Australian public. The ANMRC was able to bridge the gap effectively between research and operations at a time when the science was moving at a very rapid pace. It is interesting also to note as a result of close collaboration with the Bureau of Meteorology NMAC, that that forecast and analysis centre became the first to implement a spectral model operationally and also the first to input locally derived direct readout data into its regional analysis and prognosis scheme.*

For my own part I was able to take advantage of these surroundings and to work on projects that ran the gamut of the ANMRC's interests. Initially I worked on a variety of problems associated with the remote sensing of temperature and moisture profiles, from satellite measured infrared and microwave radiances, and also with the sensing of surface pressure with an active sounder. These interests were naturally combined with analysis work both on a hemispheric version of the three dimensional variational analysis scheme and in the four dimensional assimilation project, where the optimum use of asynoptic satellite data was a goal. Involvement with analysis and the Spectral Group also led to an interest in hemispheric climatology and active participation in developing a full hemispheric climatic atlas from the hemispheric numerical analyses.

Finally, I believe the ANMRC has functioned effectively in an area which required the linking of data retrieval, analysis and forecasting into a single system. In future years when remote ground based temperature and moisture profilers abound and are used in conjunction with space based active and passive sounders for input to our numerical analysis and prognosis schemes, we will remember ANMRC was a centre that held and worked towards such a vision. It has been my pleasure to contribute to that organization.

L.M. LESLIE, BA MSc PhD, 1970+

Lance joined the CMRC in August 1970 from Monash University. His major contribution has been in limited area modelling, advancing the Centre's Australian region forecasting model. His more recent work has been in the development of the movable fine mesh Australian region model. Other areas have included studies of mesoscale phenomena, and statistical correction procedures for numerical models (both in collaboration with Monash University), and more recently the statistical prediction of weather elements (in collaboration with A. Miller of CSIRO Division of Mathematics and Statistics).

Lance made a number of overseas trips. He spent ten months in 1973 working at the British Meteorological Office and visited Sweden and Finland. He made five shorter term visits varying from one to three months visiting universities and research institutes in the UK, Sweden, Finland, West Germany, the USA, Canada, France and Japan.

L.W. LOGAN, BSc, 1976+

Les was appointed as a Computer Systems Officer with ANMRC early in 1976. He has been attached to the Weather Research Group; on its dissection he worked in the Medium Range Prediction Group and more recently with the Regional and Mesoscale Prediction Group. He has provided extensive programming support in mesoscale modelling with particular emphasis on upgrading the operational regional system.

R. MAINE, MSc, 1969–1970

Ross was a foundation member of the CMRC staff coming from the Bureau of Meteorology (Head Office). He was responsible for much of the early initiative in developing and establishing the first regional operational numerical forecasting system in the Bureau prior to the formation of the Centre. He continued this work in the Centre, in particular developing the filtered baroclinic model for the Australian region.

In 1970 Ross was Acting Officer-in-Charge of the Centre for two months (April to June). He returned to the Bureau in January 1971 as Assistant Director of the ADP Division. He adds these comments:

The 1968/69 period in the then Central Office of the Bureau of Meteorology was exciting and full of potential for these were the years during which the Bureau's first large scale computers (then dual IBM 360/65s) were installed.

The business of numerical meteorology had been well underway for several years in the Bureau and as computing is the life blood of numerical meteorology the numerical modellers (then a very small group from the Bureau Research and Development Branch, viz. Ross Maine and Bob Seaman and later Doug Gauntlett and David Hincksman) foresaw a new era for meteorology in Australia. Under the leadership of such personalities as Gerry O'Mahoney and Bill Gibbs (Director of Meteorology) the dual 360/65 system became the basic hardware for the CMRC, which was born shortly after the second 360/65 was installed.

Although automated multi-level numerical analysis and a barotropic 500 mb prognosis system had already been implemented in the Bureau, CMRC was formed under the drive of G.B. Tucker, its first Officer-in-Charge, who began work immediately organizing the Centre. Meanwhile the development groups continued improving the analysis system and devising a seven-level operational filtered baroclinic prognosis model. Shortly thereafter development commenced on a primitive equation model. Most of these models were based on extensive work already carried out by US workers (such as Cressman, Shuman, Smagorinsky, O'Neill) but special developments were required for southern hemisphere use.

At the working level CMRC maintained a close relationship with the Bureau's National Meteorological Analysis Centre (NMAC) for it was obvious that if the Bureau was to obtain value for money from CMRC its products would need to be useable directly in forecasting practice.

The early years were intensely exciting for one was aware that our work was close to the leading edge of meteorological and computer science. Consequently there was a race against time to ensure that results were exchanged effectively with other co-workers and were reported to operational meteorologists generally so that their views could be considered.

I am sure these attitudes continued and matured during the seventies, for the ANMRC, as it was soon to be known, continued to develop into an international research centre of high standing.

B.J. McAVANEY, BSc PhD, 1971+

Bryant joined CMRC in February 1971 from the University of Adelaide. His earlier years at the Centre were involved with the assessment and further development of the spectral model; demonstration of the viability of the spectral model for general circulation studies was a major contribution by Bryant. In mid 1979 the Tropical Research Group was established under Bryant's leadership. The major achievement of this group has been the development and successful operational trials of an objective analysis scheme for the Australian tropics. For their joint publication on this work in the Australian Meteorological Magazine in 1981, Bryant and Noel Davidson shared the first Priestley Medal to be awarded, for 1981–82.

In 1977 Bryant visited the USSR for six months under the Australian/USSR Science Agreement. He spent four months at the Institute of Atmospheric Physics in Moscow and two months at the Computing Centre of the Siberian Academy of Science in Novosibirsk. A second long-term visit was undertaken in 1980–81 to Tallahasse, Florida, USA, where Bryant worked for 13 months with T.N. Krishnamurti at Florida State University on tropical numerical weather prediction. More recently (April to June 1984) he visited GFDL, USA to implement the ANMRC spectral model on a CYBER 205 computer, prior to its use on the same machine recently acquired by CSIRO.

Bryant includes the following comments:

My first awareness of CMRC/ANMRC came from a lecture delivered to the South Australian Branch of Australian Institute of Physics by Dr. C.H.B. Priestley some time in 1969. The problems he described seemed exciting and the environment in which to solve them was alluring, so on completion of my PhD thesis at the University of Adelaide I applied to join this exciting new creation. Some 13 years later I still find the ANMRC an exciting place to work, bustling with enthusiasm to get on with the job; my original decision to make the change from experimental upper atmospheric physics to numerical meteorology was a good one.

As one of the CSIRO contingent with the ANMRC there have been times when this has been a disadvantage in dealing with both parties. For example when working with colleagues within the Bureau of Meteorology attempts at 'short circuiting' procedures to get things accomplished have often failed when it was realised the interaction was not completely 'in house', one party being a CSIRO employee. On the CSIRO side there have also been problems because of the apparent scorn in which numerical modelling is held by many self-labelled 'pure' researchers. Life as a numerical modeller also has been made more difficult because of the downgrading by other scientists of the computer skills that a good modeller must have if he is to get the absolute best out of the computer to which he has access. A well constructed numerical model should at least be considered in the same light as a well constructed and innovative piece of experimental equipment!

Because of the independent nature of the CMRC/ANMRC, excellent rapport with operational meteorologists in the Regions has been possible. Personally I have found my involvement with the Regional Meteorological Centre in Darwin most stimulating, as compromises in our mutual interests were reached. A positive sense of achievement has resulted from the provision of a system which has satisfied some of the pressing needs of operational meteorologists and also is an extremely useful research tool. I can only hope that the emergence of the BMRC nurtures this type of rapport and lets it grow in many other areas.

J.L. McBRIDE, MSc PhD, 1974–1983

John's introduction to the CMRC was as a vacation student in 1970–71. He joined the Centre in 1974 working on the development of the hemispheric and regional versions of the primitive equation forecasting model. From 1976 John spent three years on study leave to undertake a PhD on tropical cyclones at Colorado State University, USA, and in early 1979 was appointed to the Centre as a Research Scientist. Here he studied convective and larger scale interactions, the Australian monsoon, the climatology of Australian region tropical cyclones, and weather systems other than tropical cyclones in the tropics. In October 1980 John visited the People's Republic of China, and Japan for several weeks. Other short term visits included Denpasar, Indonesia, in 1981, and Dacca, Bangladesh, in 1982.

With the uncertainties following the Centre's final review John resigned from CSIRO in May 1982 and returned to the Bureau. He was again attached to the Centre until May 1983 when he departed to undertake further research at Colorado State University.

In John's words:

I first came to CMRC as a cadet meteorologist in the summer of 1970–71. I worked then with Neil Streten and the late Sandy Troup, assisting in the data reduction for their synoptic climatology of mid latitude oceanic cyclones. Back then, Neil warned me that **every** *young aspiring cadet had visions of a grand and glorious scientific career. Years later I went back as a Meteorologist Class 1, working first with Bill Kininmonth and then with Doug Gauntlett on the hemispheric grid P.E. model. I left again and returned again, this time as a CSIRO Post Doctoral Fellow. This led to three exciting years' research during which Bryant McAvaney, Noel Davidson, Neville Nicholls, Tom Keenan (Bureau) and I documented many of the basic observational features of the Australian monsoon circulation. Once more I left; once more I returned, this time as an acting-Meteorologist Class 3. It's been said I keep coming back to CMRC/ANMRC as no one else in Australia is willing to employ me.*

The success of CMRC/ANMRC as a scientific unit, and as a positive developmental force in Australian meteorology, is beyond question. This can be attributed to many factors: the atmosphere of intellectual freedom; the encouragement of younger scientists by the OIC's and by the senior staff; the existence of a separate tea room for yarns of football, politics, finite difference schemes and one-dimensional cloud models; the lack of formality and the very relaxed attitude to strict working hours; the encouragement to travel on overseas scientific visits; the good mix of observational, analytical and numerical scientists on the staff; the strong visiting scientist program, and the co-operative seminar program with other institutions.

Somewhere along the line I learned to do my science fearlessly and to enjoy every minute of it. Since most of my career has been at CMRC/ANMRC, I probably learned it there. For this I am grateful to my many colleagues from that institution over the last 13 years.

J.L. McGREGOR, BSc PhD, 1975+

John was appointed as a Research Scientist with the ANMRC in July 1975. His earlier work was directed towards the staggered grid reformulation of the Australian region primitive equation (ARPE) model, its implementation into NMAC operations, and to convective cloud parameterization schemes. Subsequently he made several diagnostic studies based on the ARPE model, and more recently has made further refinements to this model and the spectral model. Recent research on limited area initialization is now being used operationally in the Bureau.

John spent September 1979 at the University of Wisconsin to implement and test the equivalent of the ARPE model developed at ANMRC for the North American region. Currently he is spending six weeks at UW as a visiting scientist.

G.A. MILLS, MSc, 1975–1982, 1984

Graham joined the ANMRC from the Adelaide Regional Forecasting Centre of the Bureau in late 1975. His major work involved modification of the analysis programs for the Australian region and a number of analysis prognosis cycling experiments to assess the impact of data available during FGGE, including data sent from the University of Wisconsin, USA.

Graham spent 11 months in 1981 at the University of Wisconsin continuing the Centre's collaborative research of recent years. From mid 1982 he was with the Research and Development Branch of the Bureau, and in October 1984 rejoined the Centre.

R.L. NAIDOO, BSc, 1983+

Naidoo joined the Centre as a Computer Systems Officer and later as a Meteorologist, coming from Florida State University, USA, in August 1983. He has been working on further development of the spectral model. Prior to joining the Centre he also spent ten months in Sweden in 1981–1982 contributing to the FGGE IIB data processing.

N. NICHOLLS, MSc PhD, 1975–1984

Neville joined the ANMRC in June 1975 from the Research and Development Branch of the Bureau of Meteorology. During the past nine years at the Centre he has worked in the Diagnostic Studies Group developing statistical methods for long range forecasting and making a number of related observation-based studies with emphasis on El Nino and the Southern Oscillation.

He undertook a six week visit overseas to the UK and USA in August-September 1978, and a further visit of two weeks to the USA in November-December 1982. In 1981 he held the WMO position of Consultant in Long Range Weather Forecasting for four months located at Badan Meteorologi dan Geofisika, Jakarta, Indonesia.

While at the Centre he completed his MSc and PhD at the University of Melbourne. He offers the following from Petronius (A.D. 66) as a valedictory statement on ANMRC:

We trained hard . . . but every time we were beginning to form up into teams we would be re-organized. I was to learn later in life that we tend to meet any new situations by re-organizing . . . and a wonderful method it can be for creating the illusion of progress while producing inefficiency and demoralisation.

P.F. NOAR, MSc, 1970–1975

Peter joined the CMRC in November 1970 from the Tasmanian Regional Office of the Bureau, to work in the interface area between Bureau operations and CMRC research. This involved collaboration with the NMAC for real and non-real time trials of the Centre's forecasting models and their subsequent assessment. Peter's comments appear in an earlier chapter of this report.

Peter also experimented with a planetary boundary layer model, based on one from NMC Suitland, USA, for use in air pollution potential prediction in the Australian region.

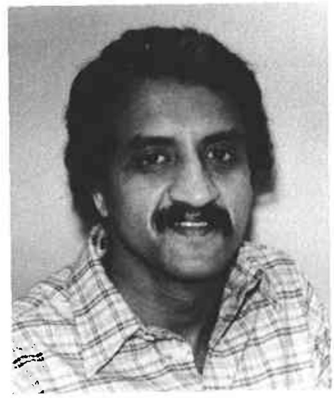
For several months in mid 1972 Peter visited a number of overseas institutions involved in the application of numerical weather prediction to the operational programs of national weather services.

He joined the NMAC of the Bureau in March 1975.

R.J. ORMEROD, BSc, 1980–1981

Robin, a PhD candidate from the University of New England, NSW, was temporarily employed by the Centre for seven months. He assisted in an investigation of predicting the Australian monsoon onset, and rain systems in the tropics other than tropical cyclones.

K. PURI, BSc PhD, 1972+



Kamal joined the Centre from the University of Manchester in February 1972. His work has been in the development and application of the spectral model for weather prediction, general circulation and assimilation studies. More recently he has contributed substantially in the area of normal mode initialization examining its detailed characteristics in the tropics.

In 1974 Kamal spent several weeks visiting a number of institutes in Denmark, the UK, Canada and the USA. He spent 14 months in 1978–79 at NCAR, Boulder, USA, and was instrumental in the adoption of the ANMRC spectral model as the NCAR Community Climate Model. He made a brief return visit in October 1980, and also visited GFDL at Princeton University. Subsequently he was appointed as a visiting scientist there for 13 months in early 1983.

Kamal's comments bring to memory, among other things, some of the more light-hearted times at the Centre:

Having been with CMRC/ANMRC for more than 12 years qualifies me to be a member of the select group of the Centre's 'old timers'. During these years I have had the great privilege of participating in the Centre's evolution to become a major force in Numerical Weather Prediction. It is not my intention here to engage in back patting regarding the Centre's scientific achievements — that is best left to more objective observers. I shall concentrate mainly on other day-to-day factors which made the Centre such an attractive place to work.

I was very fortunate to be a member of the Spectral Modelling Group and share in the excitement of the development of the first spectral model for numerical weather prediction and general circulation studies. For me, two aspects of this work were particularly satisfying. One was the acceptance of the spectral model as the Bureau of Meteorology's operational model — a first. The second was the first long integration with fixed January conditions with a global spectral model. The latter was carried out on a shoestring budget which left very little margin for error. We were thus forced to conduct very close monitoring of the integration with lengthy daily discussions of the previous night's runs. These discussions which were carried out in an atmosphere ranging from deep depression on one day to high excitement the next, were extremely stimulating and educational.

A very important factor in the Centre's development was the deep commitment towards the Centre of most of its employees. This commitment manifested itself both at the scientific and social level. An example of this enthusiasm was the Centre's participation in the CSIRO swimming competition and winning it for three years against much larger Divisions. The involvement of swimmers and non-swimmers had to be seen to be believed. Social events were organized regularly and well attended. There was active support for the social committee's projects, such as its involvement in enterprising activities as the use of waste computer output to finance the Christmas parties, and catering for morning and afternoon teas at the IAMAP, 1974 meeting in Melbourne. Most of the considerable amount of money raised in the latter project was donated to the Darwin disaster fund. The highlight of the social scene was the 'Thank God It's Friday Evening' Club whose meetings were originally held at the City Court and later moved to the Continental (local hotels). These meetings, long and short, were well attended and always interesting and lively, especially the longer ones.

It is unfortunate that in the 'interest' of rationalization of atmospheric research in Australia it has been found necessary to disband ANMRC. It is doubly unfortunate because at the time *of the last review the Centre was at its strongest in terms of personnel and expertise. However, it is hoped that whatever replaces the Centre will be able to recreate the sense of excitement and purpose that was provided so successfully by the CMRC/ANMRC. It will be a difficult, hopefully not impossible, task. For me however, the CMRC/ANMRC will always be something special.*

J.M. SARDIE, BSc PhD, 1984+

Joe joined the Centre on May 1984 after completing a PhD at Pennsylvania State University while on leave from the Bureau of Meteorology's Sydney Regional Forecasting Centre. He is working with the Medium Range Prediction Group.

R.S. SEAMAN, BSc, 1969+

Bob was a foundation member of the CMRC staff in 1969 coming from the Bureau where he had been involved with the early development of numerical analysis and weather prediction systems.

In the Centre Bob has been involved with most areas of objective analysis research on which the Centre has concentrated; for example the design and implementation of a southern hemisphere objective analysis scheme, as well as refinements to it and the Australian region analysis-prognosis system when the primitive equation models were developed. Bob designed and carried out many other projects to overcome problems arising from the lack of data for the southern hemisphere, particularly conventional data at upper levels. In recent years he has spent considerable time developing four dimensional data assimilation procedures for the spectral forecasting model. This scheme has been used in important experiments utilizing the FGGE data base and has now been expanded for operational application.

Since April 1983 he has been leader of the Medium Range Prediction Group. For five weeks in 1970 Bob visited a number of scientific centres concerned with meteorological analysis in the USA and UK. He spent 13 months in 1978–79 at the ECMWF as a research consultant contributing to the earliest tests of the ECMWF four dimensional assimilation system.

Bob's views on a number of aspects are included in the following:

SOME SUBJECTIVE THOUGHTS ON CMRC/ANMRC 1969–84

The beginning

"My own belief, which some others do not share, is that [in its decision to establish the CMRC] on this occasion the government was wiser than its scientific advisers." (Priestley, 1982)

Count me as one who supports the Priestley view. But my reason, with the benefit of hindsight, differs from Priestley's. In the late 1960's, the attitudes to research which prevailed in the CSIRO on the one hand, and in the Public Service and the Bureau on the other hand, differed even more radically than they do now. Such was this disparity in attitudes, that I believe the active participation of CSIRO was essential at that time for a satisfactory research environment.

A tribute

And indeed, for its whole life, the key to the Centre's success was its working environment. An important element of this environment, particularly in the early days, was the deliberate encouragement of diverse attitudes, a policy not notably in evidence in the Bureau during the 1960's.

Many people, including all the OIC's, deserve credit. But one person stands out. Those of us who were foundation members, witnessed the single-mindedness with which Brian Tucker, in the face of hostility from the Bureau, established a new institutional spirit and identity. Without him, there simply would not have been a Centre. Whatever else has happened since, for those first few years, Brian, many thanks.

The two cultures

A prime reason for setting up the CMRC was to promote interaction between research and operations. It certainly did that, and the result was undoubtedly of mutual benefit. But it was not achieved without conflict between the more extreme attitudes and personalities on either side. The culture shock was probably greatest for those young scientists in the Centre, whose work brought them into contact with some of the more reactionary elements in the Bureau. The attitudes moulded by these early encounters are clearly in evidence today.

It worked the other way too. In my own case, despite having come from the Bureau's Research and Development Branch, I never quite came to terms with the more extreme manifestations of the CSIRO 'publish or perish' attitude. Undoubtedly, publications contributed significantly to the Centre's international reputation, if you believe that the latter has some intrinsic value. (And obviously many do believe it — we now have the Bureau talking about 'parity of esteem' for BMRC.) But arguably the Centre's more practical and tangible achievements (products used by the Bureau and others) occurred in spite of, not because of, the CSIRO attitude to publications.

The mushroom principle

What publish or perish is to the research scientist, the mushroom principle is to the administrator. The former attitude is happily waning; the latter is alive and well. The agreement to disband the Centre was reached almost a year before its announcement to ANMRC staff (the latter closely following a similar announcement in the American Meteorological Society Newsletter).

The predictable reasons given for keeping us in the dark for so long, were to prevent the breakup of research teams and to maintain staff morale. Readers are invited to consider for themselves these reasons, both from the aspect of morality and from the aspect of effectiveness. My only comment is that in an elitism contest, our top administrators would leave the average research scientist for dead!

The end

At the time of writing, it appears that more than three years will have separated the decision to disband the Centre, and its actual closing. A prolonged and messy end. When my own time comes, I hope it's quicker.

L.F. SIMPSON (nee Clear), BSc, 1973–1976

Lesleigh, a Computer Systems Officer, joined CMRC in March 1973. She worked with both the Spectral Modelling Group and the General Circulation Group. Lesleigh resigned in March 1976.

R.W. SIMPSON, BSc PhD, 1972–1975

Rod joined the CMRC in March 1972 from the University of Queensland. He carried out experiments using a general circulation model of the atmosphere to investigate the importance of warm sea surface temperature anomalies to weather conditions over Australia. Rod resigned from the Centre in March 1975.

S.H. SOUTHAM, BSc, 1976–1980

Stewart joined the ANMRC as a Computer Systems Officer in March 1976. He was attached to the Diagnostic Studies Group and later the Climate Research Group. He resigned from the Centre in February 1980 to take up a position with Alcoa.

N.A. STRETEN, BSc DSc DPA, 1969–1983

Soon after its establishment in 1969, Neil joined the CMRC from the Bureau (Head Office) to develop expertise in the area of satellite meteorology. This he did, researching many aspects of southern hemisphere circulation patterns and climatology. These included cloud vortices, characteristics of extreme seasons, sea surface temperature effects on seasonal climatic features, and the influence of Antarctic sea ice on circulation patterns. Neil was leader of the Diagnostic Studies Group from its inception in February 1976 until his departure in 1983.

Neil held the position of Associate Professor of Meteorology at the Geophysical Institute, University of Alaska for 14 months from mid 1973. He also visited various research institutes in the UK, USA, Japan and France in August-September 1975, and in the UK, Europe and South Africa in 1981.

Neil was awarded a DSc from the University of Melbourne in 1983. He was appointed to the new position of Assistant Director, Executive Branch in the Bureau in March 1983.

He contributes the following:

ON THE PASSING OF ANMRC

Most organizations like all living things go through stages of youth, maturity and old age. ANMRC, cut short in its early years, perhaps reached barely the third of the seven ages of man. Had it at least become "the Soldier, full of strange oaths . . . sudden and quick in quarrel", it may have been able to defend itself more professionally and go on to maturity. Its dealth in childhood does not mean an illness or poor constitution, but the impatience of its parents, themselves suffering straightened means and a less than ideal marriage. This is not to say that either parent was inherently cruel or ill-dispositioned. The process of torture (by multiple review) and ultimate martyrdom of ANMRC must be seen as a reflection of the existence of an active adversary system in the world of Australian science administration. Such a system, which would be seen to be healthy in some circles, takes its motto from commando training parlance — "get him before he gets you". Working scientists are rarely proficient in jungle warfare.

There is little point, however, in considering what might have been. To be optimistic, it has to be believed that the death of the Centre will lead to the spreading of its ideals to the organization which follows it, and to those to which its members are dispersed. It was a unique phenomenon in that for the first time CSIRO and Public Service scientists worked jointly on research projects of originality and significance within a single organization. However, after this experience, it is unlikely that we will look upon its like again.

One might ask, does it matter in what type of organization research is performed. There is reason to believe that it does. To a research worker the necessities of life are first the freedom to evolve his research abilities and interests, and secondly, a reasonable career structure. The one advantage which ANMRC gave to its research staff from the Bureau of Meteorology and which the Bureau could not give internally was continuity of project and line of research leading to the development of expertise and substantial international standing. This was no fault of the Bureau. Public Service career structure with emphasis on filling of positions which become temporarily vacant within a hierarchy, the points scored for acting in such higher positions (which is viewed as of great importance by the mechanism of Promotion and Appeal), and indeed, the sense of justice being seen to be done, which are all part of the Public Service personnel scheme, have their dark side in militating against the steady development of a research career. For various reasons, (initially as a policy, and later as a habit) Public Service professional staff in ANMRC were not often seen as possible candidates for such positions and were thus left to continue their research work undisturbed. This provided a continuity to research programs, but also, in a number of cases, it may be argued that it restricted career prospects. Thus, ANMRC provided continuity but a less than ideal career structure.

CSIRO staff within the Centre experienced no such problems. 'In situ' promotion for good research and the potential 'Principal Research Scientist bulge' in staffing structure (admittedly not achieved in the short life of the Centre) enabled continuity of program and career prospects to be maintained jointly. Such a costly scheme has been, of course, anathema to the Public Service Board.

It may be, that after many years, the Board has recognized that a research structure is quite different to the rest of the Public Service, and that some special arrangements have to be made to maintain an active, developing and mature research organization, while also providing adequate career prospects to its researchers. If, in some small way, ANMRC helped to bring home this point so that efficient principles of staff structure for research in the Public Service in general, and the Bureau of Meteorology in particular, can be developed it will not have existed in vain.

Over the door of any new research organization within the Public Service ought to be carved in massive letters 'CONTINUITY and CAREER'.

R.L. THURLING, MSc, 1971+

Bob commenced duty with CMRC in June 1971 as a Programmer. Subsequently he contributed the major programming expertise required in conducting the spectral model trials in the early seventies, and its final operational implementation in early 1976. He has worked in most areas of the Centre's research program becoming the senior Computer Systems Officer in the latter part of 1977. Since mid 1983 Bob has been on temporary transfer to a senior position within the Bureau of Meteorology.

A.J. TROUP (late), BSc, 1969–1971

Sandy, as he was known, was seconded to the CMRC from CSIRO Division of Meteorological (later Atmospheric) Physics for two years from late in 1969. His main area of research, in collaboration with N. Streten, was the development of a synoptic climatology and classification of southern hemisphere cloud vortices based on satellite imagery. Sandy's death in 1983 was a great loss to meteorology and to his colleagues at ANMRC.

G.B. TUCKER, BSc PhD, 1969–1973

Brian was the foundation Officer-in-Charge of the CMRC, from April 1969 until March 1973 when he became Chief, CSIRO Division of Atmospheric Physics. During those first years of the Centre's life he selected many of its early staff members and established the main research directions, overseeing the initial developments in NWP including an operational analysis and prediction system for both the hemisphere and region. Brian's comments on this period appear in an earlier chapter of this report. His own research included a number of investigations based on the Laverton Serial Sounding data and the development of a time average model of the atmosphere.

Brian spent several months in mid 1970 visiting major overseas research institutes engaged in numerical meteorology. In 1971 he attended an IUGG meeting in the USSR, and a GARP planning conference in the USA, as well as visiting a number of research institutes in Japan, Switzerland and the UK. He was elected to the Joint Organizing Committee of GARP in 1972, and was a member of the ANMRC Advisory Committee from 1974 until its disbandment in 1979.

M.E. VOICE, MSc 1969+

For eight months from June 1969 Mary was seconded to the CMRC from the Bureau of Meteorology. At that time she was completing her MSc at the Melbourne University; she became a substantive member of staff early in 1970. After some experience in analysis research she joined the General Circulation Group in 1972 where in collaboration with Barrie Hunt she developed the 18-level Fourier (or semi-spectral) model, which has been used for studying drought producing mechanisms.

Mary spent two weeks in 1980 attending a course entitled "Climatic Variations: Facts and Causes" held at Erice, Sicily, Italy. She also gave freely of her time to talk to outside groups and schools on meteorology.

Since mid 1983 Mary has been on temporary transfer to the Scientific Services Branch of the Bureau. Being the poet of the Centre she has treated us to some verse for this valedictory report:

BITTER AND SWEET

We started in secret and ended the same
In many ways that was a shame
For the idea was good
A joint research place should
Fill a much needed role in the Aus weather game.

Thus there was born a chimera child
Starting its life unreconciled
To us on the inside tier
It seemed like a great idea
But it sometimes drove the principals wild.

Those principals headed their fields with pride
But their personal discord they could not hide
A sign of the passions
That science always fashions
Who said science only had a calm rational side?

From the start the Centre's name was a curse
It was always a mouthful and what was worse
It caused the Bureau pain
And again and again
There were fights on the size of the fiscal purse.

The Centre was very much on the fringe
Did that give us a mandate to whinge
About 'ivory tower' shots
From practitioner slots
And from those with a cultural cringe?

Pressure from without led to bonding within
At least until the money grew thin
Thus for many years
There were very few tears
For we thought "A great place to work in"

I saw that the tussles for power grew large
There were those who preferred not to plead but to barge
I was caught oft enough
Twixt the tough and the rough
And the Officers — several — In Charge.

I hated this side of the Centre's esprit
Why can't people just live and let be
It seems so to me
That success personally
Comes from self and science integrity.

Remember Thurling's Arthur Ling
When the node was in its primal swing
When Bob Seaman teased
Much more than some pleased
And our alter egos did their thing.

Remember Dingle's lovers' farm —
I guess he didn't do much harm
At least to the Centre
I ask in absentia
Did others hold such fatal charm?

Ah, those were the days of carefree malaise
Of Watson's and Toto's and other cafes
Of youthful dreams
Life is what it seems
Gone now for ever are those golden days.

I never deep down thought the Centre would close
I was a little naive I suppose
A new circumstance
I'm takin' a chance
In the so-called Scientific Services Branch.

In the last few years the Centre was drained
The 'light on the hill' grew weak and waned
The future was dim
The Bureau was grim
In its fold it wanted the Centre contained.

We, denied knowledge of crucial decisions
Unaware of some death-knell incisions
Now bitter we chime
We wasted our time
On reviews that were rubber-stamp abscissions.

The Centre had characters in the crew
I'll only have space to mention a few
A melting pot range
From the suave to the strange
And heavily dosed with a wild Irish stew.

The person who kept the Centre alive
Through good times and bad her work would arrive
That there was Gayle
A tribute I hail
She typed everything faster than time-warps can drive.

The Gauntlett that fitted the Centre just right
Like a glove you might say, perhaps a bit tight
He became O.I.C.
Some would say oh — I see
He may not be big, but he's heavy not light.

Reg Clarke indeed was no-one's fool
But almost stubborn as a mule
He had fights with Barrie
On details don't tarry
But the air took many years to cool.
(CO_2 increases notwithstanding)

The spectral faction brooked no claim
Or challenge to its self-claimed fame
To run faster AND cheaper
And be the world's keeper
For the players there t'was a deadly game.

Remember Brian Tucker's flair
For liar dice in a lunchtime lair
And Peter Noar's penchant
For horror movies trenchant
And Tony Barker's air of devil-may-care.

It's sad to see the Centre must go
But science will always go on, that's so
We want action these days
To cut through the maze
And forge forward with structures we know.

The Centre was part of my life — one part
But the science, the teaching, the weather as art
Come close to my soul
As a life task that's whole
And governed my outlook and style from the start.

These interests that beckoned me far and afield
Meant that to research alone I would not yield
What with careers talks for girls
And public education whirls
My feminine viewpoint was barely concealed.

Where does the future decree I shall turn
Can the Bureau accommodate women who burn
With radical views
In conservative pews
Can I reach ambitions with which I yearn?

Perhaps a poet I should have been
Leaving science research to those who are seen
As traditional doers
Then I could have cleaned sewers
Or danced o'er Elysian fields so green.

Farewell to the Centre, farewell to its cast
Farewell to the concept that did not last
A unique venture was tried
Now its concord has died
Farewell to the Centre, farewell to the past.

P.J. WEBSTER, FRMIT PhD, 1971

Peter joined the CMRC in March 1971 as a Meteorologist from Massachusetts Institute of Technology, Cambridge, USA where he had completed his PhD. He investigated tropical problems such as the influence of extra tropical forcing on low latitude circulations and the Walker Circulation. Peter resigned in December 1971 to take up an academic position with UCLA, Los Angeles, USA.

N.C. WELLS, BSc PhD, 1975–1978

Neil was the first oceanographer to join the Centre, coming from the University of Reading, UK, in October 1975. He worked on developing and assessing the suitability of numerical models of the ocean for coupling with atmospheric models. Collaboration with Kamal Puri yielded an early demonstration of a coupled atmosphere-ocean mixed layer model.

Neil returned to the UK in November 1978 to take up a position with the Department of Oceanography at the University of Southhampton.

His comments:

I would much prefer to be writing about the future of the ANMRC, than contributing to this valedictory report. I feel that it is a pity that a young research centre with considerable talent, should be disbanded at a time when the efforts of past years are coming to fruition.

Professionally, I felt that the Centre was a unique research laboratory. This uniqueness was attributed to its physical location with the Bureau of Meteorology, in an environment where daily contact between ANMRC researchers and the professional meteorologists 'on the bench' could take place. This type of contact is of vital importance for both the researcher in NWP and the meteorologist. At the same time the Centre and its staff had its independence from the Bureau of Meteorology which gave the necessary freedom for scientists to follow up new and challenging ideas, such as the spectral model. Furthermore, there was the necessity for each scientist to prove his research capability by the publication of his work in the international meteorological journals, which in turn led to a good reputation for the Centre, both in Australia and overseas.

Personally, I benefitted by this liberal attitude and the helpfulness of many colleagues in the Centre. In particular, I was able to follow my own line of work on coupled ocean-atmosphere models without hindrance from my peers. Although these experiments were limited, this work gave an indication of the interesting interactions between ocean and atmosphere and the possibilities for short-term climate prediction. Furthermore, I now realise after returning to an academic department, that this type of work can only be done successfully in an environment consisting of both research meteorologists and oceanographers.

However, it would be dishonest of me if I were to give the impression that I do not have criticisms of ANMRC during my three year appointment. As a member of the Climate Research Group, I felt that the problems tackled by the group, although of undoubted scientific merit, were too diverse for the size of the group. Climate research is a more complex problem than NWP, as it involves an understanding of the changing boundary conditions of the atmosphere, as well as the atmosphere itself. Because of this inherent complexity it would have been wiser with hindsight, if the effort had been concentrated on a specific area of the climate problem, perhaps seasonal and interannual variability. Furthermore, this diversity of approach resulted in considerable effort being put into the development of models before any scientific experiments could be carried out. More experiments would have been possible if the effort had been directed towards fewer models.

I also felt that many frustrations at ANMRC between 1975 and 1978 were related to the lack of computing power. Compared with similar laboratories in the USA and Europe, the computing *resources available were inadequate. It is perhaps a measure of the quality of the staff at the Centre that a high standard of research was maintained, in spite of the short-comings in this resource.*

I would like to conclude by noting that although the ANMRC did not fit neatly administratively into either the Bureau or CSIRO, it did work well as a research organization. I hope the imperatives of administrative simplicity do not inhibit Australian NWP and climate research in the future.

M.A.G. WILLSON, BA PhD, 1971–1975

Martin completed his PhD through the Cavendish Laboratory, Cambridge, UK and joined the CMRC in August 1971. His research included a study of diurnal and semi-diurnal wind variations over Australia, and statistical dynamical modelling. Martin resigned in February 1975.

E.J.A. WOLANSKI, MSc PhD, 1974

Eric joined the CMRC in February 1974 as a Research Scientist from California Institute of Technology, Pasadena, USA. He spent eight months with the Centre investigating problems associated with modelling the planetary boundary layer. Eric resigned to take up a position with the NSW State Pollution Control Commission.

J.R. YOUNG, BSc, 1969–1975

Jim was a foundation member of the CMRC being one of its programming staff. A major area of his work was the development of an improved analysis-prognosis system for Bureau operations for the hemisphere and Australian region based on the baroclinic model. Jim was promoted to a position within the Bureau in September 1975.

Administrative Officers

The Centre was unique in being a joint unit of CSIRO and the Bureau of Meteorology until 1975, and afterwards CSIRO and the Department of Science. Administratively this entailed a knowledge of not only CSIRO procedures, but also the Australian Public Service.

F.K. TIGHE, 1969

Although not formally a member of the CMRC's staff, Frank Tighe, CSIRO Division of Meteorological Physics, acted as Divisional Administrative Officer from April to August 1969, thus carrying the initial administrative load in establishing the Centre.

W.P. DOMINGUEZ, 1969–1970

Bill was the CMRC's first Administrative Officer taking up duty in early August 1969. He was successful in obtaining promotion to a position with CSIRO Division of Horticultural Research in South Australia, departing from the Centre in February 1970.

N.W. BRANSON, 1970–1976

Norm was the Centre's Administrative Officer from February 1970 to May 1976.

Norm was Secretary of the Organizing Committee for the First Special Assemblies of IAMAP/IAPSO held in Melbourne in January 1974. In May 1976 he was promoted to a position with CSIRO Division of Protein Chemistry, Parkville, Victoria. His comments on his period with the Centre follow:

My period as Administrative Officer from February 1970 until May 1976 covered almost all of the formative years of the Centre.

I had the opportunity to work with three Officers-in-Charge during my stay, and although all had significantly different personalities, whilst they were at the helm of the Centre they had to walk the tight rope between scientific integrity and the need to develop systems for immediate application. The other commonality amongst the leaders was the recognition of the importance of building and maintaining a team.

The most significant event I feel now, looking back over those early years, was that of being part of a team striving to prove to its detractors that the Centre was worth the expenditure of resources necessary for its continuance. It seems that there was always something else that could be achieved if the recources being applied to the Centre could be diverted to other more deserving projects. The Centre was an expensive Unit, if one measured cost purely in terms of short term advantage for the dollar expended. The difficulty was to get the decision makers to recognise that research of this type was expensive and long term, and needed a long term commitment from Government.

I have recognised a common trait amongst providers of resources for scientific research, which initially I had thought was peculiar only to the Centre. That is, that their common desire is to obtain some immediate return on their investment dollar. Whilst I can comprehend this desire in a non science backed organization, I have to admit still to being surprised that it exists so openly in a scientific group.

From a human relations viewpoint, the conflicts of direction and emphasis amongst the joint 'owners' of the Centre generated a cameraderie at the working level that I have rarely seen in other groups. All Centre members seemed to be charged with the same responsibility: to prove that the concept of the Centre could work. This is not to say that during this period, there were not 'normal' scientific and social conflicts amongst the close knit group of workers, but there was this apparent overriding professional purpose.

It was indeed gratifying to be part of a team which was able to accomplish both personal and team generated scientific achievement, within less than optimum environmental conditions.

J.L. GINNANE, 1976–1982

Jim joined the ANMRC as Administrative Officer in August 1976, coming from CSIRO Division of Atmospheric Physics. He successfully maintained good relationships with staff, as well as with the administrations of both parent bodies during the ANMRC years of innumerable reviews. Jim gained promotion to a position with CSIRO Victorian Regional Office, departing from the Centre in July 1982.

R.J. ABISHARA, 1982–1984

Dick was appointed as the Centre's Administrative Officer in July 1982 coming from CSIRO Division of Applied Organic Chemistry, after the decision had been made to disband the Centre. Thus, apart from normal duties, he was involved with the gradual 'winding down' procedures.

B. RIPPER, 1984+

Barry joined the Centre in October 1984 for the final few months of its operation, coming from CSIRO Division of Animal Health.

Technical and Support Staff

Three months or more

Miss C. Aiello, Stenographer/Secretary, 1984+
M.R. Brooks, Technical Assistant, 1971
Mrs D.K. Bulner, Technical Assistant, 1976+
Mrs J. Buttler (nee Grech), Clerical Assistant, 1972–1978
V. Carreto, Technical Assistant, 1981
Miss K. Choy, Stenographer/Secretary, 1983–1984
Mrs G. Clarke (nee Burt) Stenographer/Secretary, 1970–1983
Miss J. Carnegie, Stenographer/Secretary, 1984
P.G. Collie, Technical Assistant, 1975
Miss P.V. Cummings, Technical Assistant, 1981–1982
C. Donahoo, Clerical Assistant, 1973
Mrs C. Donkin (nee Bromley) Clerical Assistant, 1977–1983
Mrs M.A. Ellis (nee Lee-Archer), Stenographer/Secretary, 1969–1971
Mrs D. Farmer, Stenographer/Secretary, 1983
Miss F.J. Gilhooly, Clerical Assistant, 1982+
P.E. Hambleton, Technical Officer, 1977+
Mrs S.A. Ickeringill, Technical Assistant, 1972–1978
Mrs C. Izzard, Technical Assistant, 1975–1976

W.R. Kellas, Technical Officer, 1972–1976
Mrs B.S. King (nee Jordan), Technical Assistant, 1969–1971
Mrs H.T. Nanscawen (nee Wilkinson), Clerical Assistant, 1970–1974
D.J. Pike, Technical Officer, 1975+
P.E. Powers, BApplSc, Technical Officer, 1975+
Mrs W.M. Powers (nee Kenny), Technical Assistant, 1971–1976
Miss J. Ross, Clerical Assistant, 1974–1975
Mrs H. Scott, Technical Assistant, 1973–1976
Mrs S. Smith, Clerical Assistant, 1973
Miss P.L. Snell, Technical Assistant, 1979–1980
Ms S. South, Clerical Assistant, 1976–1977
Mrs K.P. Wier, Technical Assistant, 1971–1973
R.A. Weinert, Technical Officer, 1969–1974
Mrs A.E. Wilson, Clerical Assistant, 1975–1977
P.P. Yew, Technical Assistant, 1976–1984

Miss C. Aiello

Mrs D.K. Bulner

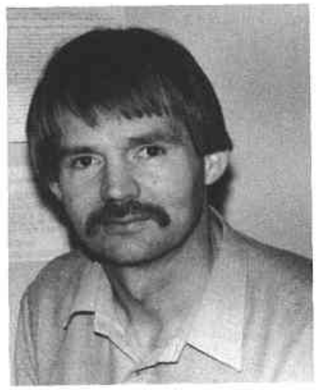
Miss J. Carnegie

Mrs C. Donkin

Miss F.J. Gilhooly

P.E. Hambleton

D.J. Pike



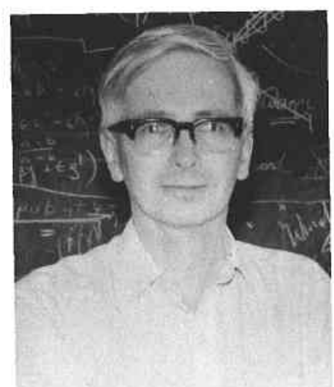
P.E. Powers

P.P. Yew

Scientific Consultants

A.J. MILLER, MSc PhD, CSIRO Division of Mathematics and Statistics, 1981+

Alan has been working one day per week at the Centre to advise on statistical problems, and has collaborated on several research projects.



G.F. NELSON, BSc, CSIRO Division of Mathematics and Statistics, 1981–1982

Graham also worked on statistical problems in collaboration with ANMRC staff for one day per week.

Vacation Students

University students, who usually had completed the third year of their undergraduate courses, employed by the CMRC/ANMRC for 8 to 12 weeks of their summer vacations.

R.C. Bell, 1969–70, 1970–71, Monash University

G.R. Budin, 1980–81, Australian National University

B.J. Davis, 1983–84, University of Melbourne

Miss J.L. Evans, 1982–83, Monash University

M.G. Hardy, 1983–84, Monash University

Miss F.M. Larkins, 82–83, Monash University
D.K.K. Lau, 1980–81, Monash University
J.L. McBride, 1970–71, University of Melbourne
Miss K.L. McInnes, 1982–83, Monash University
Miss J.A. Noonan, 1981–82, Monash University
T.J. Stevenson, 1983–84, Monash University

Special Youth Employment Training Program

Employed for 17 weeks as Technical Assistants

Miss N.G. Borovec, January — May 1982
D.G. Cameron, March — July 1982
Miss J.L. Campbell, July — November 1981
S. Catalano, May — September 1982
Miss P.V. Cummings, March — June 1981
Miss L. Cvetkovska, September 1983 — January 1984
M. James, November 1982 — March 1983
A. Leptos, July — November 1982
I.D. McRae, September 1981 — January 1982
G. Phillips, February — May 1981
Miss E.M. Renehan, November 1981 — March 1982
E. Salvatori, May — September 1983
S. Scamporlino, September 1982 — January 1983

Visiting Scientists

One week or more

Dr D.L.T. Anderson, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK, February to September 1979.
Dr L. Bengtsson, European Centre for Medium Range Weather Forecasts, Reading, UK, March 1978.
Dr W.F. Blyth, Royal Melbourne Institute of Technology, July to September 1983.
Dr D.M. Burridge, European Centre for Medium Range Weather Forecasts, Reading, UK, November to December 1980.
Dr G.A. Corby, British Meteorological Office, UK, November 1972.
Prof K. Fraedrich, Freie Universitat, Berlin, West Germany, October 1982 to February 1983.
Prof W.L. Gates, Department Atmospheric Sciences, Oregon State University, USA, August to September 1981.

Dr A.E. Gill, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK, June to August 1982.

Dr J.S.A. Green, Atmospheric Physics Group, Department of Physics, Imperial College of Science and Technology, London, UK, November to December 1975.

Dr T. Hiraki, Japan Meteorological Agency, Tokyo, Japan, September to December 1984.

Prof D.R. Johnson, Department of Meteorology, University of Wisconsin, Madison, USA, January to February 1974, February 1977, November 1981.

Dr M. Kanamitsu, Japan Meteorological Agency, Tokyo, Japan, January to February 1984.

Dr J. Kidson, New Zealand Meteorological Service, Wellington, NZ, March 1970.

Dr M.J. Manton, CSIRO Division of Atmospheric Research, Epping NSW, May 1984.

Dr K. Miyakoda, Geophysical Fluid Dynamics Laboratory, Princeton University, USA, November to December 1979.

Prof N.A. Phillips, National Meteorological Center, NOAA, Washington DC, USA, May to June 1981.

Mr D.K. Purnell, New Zealand Meteorological Service, Wellington, NZ, February 1972 to March 1973.

Dr F.G. Shuman, National Meteorological Center, US Department of Commerce, ESSA, Silver Spring, USA, June to July 1970.

Dr M. Revell, New Zealand Meteorological Service, Wellington, NZ, June to September 1984.

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