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HOUSE OF REPRESENTATIVES
STANDING COMMITTEE ON
AGRICULTURE, FISHERIES
AND FORESTRY

THE BUREAU OF METEOROLOGY SUBMISSION TO THE

HOUSE OF REPRESENTATIVES STANDING COMMITTEE ON AGRICULTURE, FISHERIES AND FORESTRY INQUIRY INTO FUTURE WATER SUPPLIES FOR AUSTRALIA'S RURAL INDUSTRIES AND COMMUNITIES

SEPTEMBER 2002

SUMMARY

The Commonwealth Bureau of Meteorology is responsible at national and state levels for a number of aspects of the assessment and management of Australia's water resources and for a range of related hydrological services including flood forecasting and warning. It therefore has a major interest in the subject matter of the Inquiry.

The purpose of the Bureau is to contribute to Australia's social, economic, cultural and environmental goals through the performance of the functions of a National Meteorological Service "in the public interest generally and, in particular, … for the purpose of assisting persons and authorities engaged in primary production, industry, trade and commerce" (Meteorology Act 1955).

There are strong linkages between meteorology (weather and climate) and water. The most fundamental linkage results from the interactions between the atmosphere and the land and ocean surfaces through the hydrological cycle. The Bureau's observation and data collection systems are an integral component of water resources assessment practices, albeit primarily targeted at the atmospheric phase of the hydrological cycle and precipitation at the surface. Detailed understanding of weather and climate is essential to a sustainable approach to water resources management in Australia. The application of services based on sound meteorological science to operational water resources management processes and procedures offers significant potential benefits to Australia's rural industries and communities.

This submission identifies a number of key issues of importance in relation to future water supplies for Australia's rural industries and communities from the perspective of the Bureau of Meteorology and its national and international responsibilities for monitoring, research, and provision of meteorological and hydrological services. The submission also responds directly to the Terms of Reference of the inquiry based on the statutory and historical basis for the role of the Bureau. The key issues raised by the Bureau in this submission are:

- The benefits of long term monitoring of weather, climate, surface water and groundwater
- The need for appropriate standards and consistency in data collection
- The benefits of improved management and research capabilities
- The limitations of cloud seeding as a water resources management tool;
- The fundamental role of good observations and networks in the detection, monitoring and prediction of climate variability and change;
- The scientific basis for, and limitations of, weather and climate forecasting;
- The status of climate forecast verification, and the need to undertake rigorous forecast assessment prior to the adoption of new systems; and
- The current Bureau of Meteorology public good prediction service - strengths, weaknesses, and scope for improvement.

The information and services provided by the Bureau in support of Australia's agricultural activities play an important role in both the physical/structural elements of water resources management, such as dams and irrigation systems, and in providing tools to enable water resource managers and farmers to better manage a valuable and scarce resource. The incorporation of Bureau weather, climate and hydrological monitoring and forecasting tools in the decision support systems used by water resources managers and users will assist in sustainable management of the resource.

TABLE OF CONTENTS

Attachments

HOUSE OF REPRESENTATIVES STANDING COMMITTEE ON AGRICULTURE, FISHERIES AND FORESTRY

INQUIRY INTO FUTURE WATER SUPPLIES FOR AUSTRALIA'S RURAL INDUSTRIES AND COMMUNITIES

1. INTRODUCTION

The purpose of this submission is to inform the House of Representatives Standing Committee on Agriculture, Fisheries and Forestry Inquiry into Future Water Supplies for Australia's Rural Industries and Communities on the role of the Commonwealth Bureau of Meteorology in contributing to the assessment, planning, development and operational aspects of Australia's water resources. In particular, the Inquiry has requested submissions on "the adequacy of scientific research on the approaches required for adaptation to climate variability and better weather prediction, including the reliability of forecasting systems and capacity to provide specialist forecasts."

Knowledge and understanding of Australia's weather and climate is an integral component of the management of Australia's water resources and, as the national agency with statutory responsibility for meteorological observations (including precipitation and evaporation), the Bureau of Meteorology has an important role to play in the management activities. This submission is framed in terms of the statutory functions and responsibilities of the Bureau as set out in the Meteorology Act 1955 (Attachment 1).

Under the Act, the Bureau of Meteorology has certain national responsibilities in respect of the atmospheric, and parts of the land, phase of the hydrological cycle and, accordingly, has a key role in water resources assessment, planning and development on a national scale.

The statutory functions of the Bureau include, *inter alia*:
- the forecasting of weather and the state of the atmosphere;
- the supply of meteorological information;
- the promotion of the use of meteorological information;
- the promotion and advancement of meteorological science, by means of meteorological research and investigation or otherwise;
- the furnishing of advice on meteorological matters;

The Bureau performs these functions under the Act in the public interest generally and in particular for the purpose (*inter alia*) of assisting persons and authorities engaged in primary production, industry, trade and commerce.

2. KEY ISSUES

In compiling this paper, the Bureau has identified a number of key issues which it believes should be considered by the House of Representatives Standing Committee on Agriculture, Fisheries and Forestry in the conduct of its Inquiry. These issues include:

- The benefits of long term monitoring of weather, climate, surface water and groundwater;
- The need for appropriate standards and consistency in data collection;
- The benefits of improved management and research capabilities;
- The limitations of cloud seeding as a water resources management tool;
- The fundamental role of good observations and networks in the detection, monitoring and prediction of climate variability and change;
- The scientific basis for, and limitations of, weather and climate forecasting;
- The status of climate forecast verification, and the need to undertake rigorous forecast assessment prior to the adoption of new systems; and
- The current Bureau of Meteorology public good prediction service - strengths, weaknesses, and scope for improvement.

2.1 The benefits of long term monitoring of weather, climate, surface water and ground water

Information on the availability of freshwater resources, both in space and time, is essential for the sustainable management of the resource. The availability of surface water in Australia is primarily dependent on meteorological factors – the temporal and spatial distribution of rainfall and the role of atmospheric temperature, wind and other variables on evaporation from the land and water surfaces. A commitment to long term monitoring of the various meteorological controls and of both the quantity and quality of the resource is required to better understand and manage changing resource availability and quality under:

- Australia's extremely variable climate (spatial and temporal variability);
- Conditions of increasing pressure due to development of the resource; and
- The potential impacts of long-term human-induced climate change.

2.2 The need for appropriate standards and consistency in data collection

There is a large number of State/Territory and regional organisations and agencies with responsibility for assessing, monitoring, managing and regulating Australia's surface and ground water resources. The National Land and Water Resources Audit (NLWRA) confirmed (Australian Water Resources Assessment 2000 pp81-85, Australian Natural Resources Information 2002 pp50-53) the view that the standards, technologies and techniques used by these organisations and agencies vary widely and/or are interpreted differently. The result is that data and information management systems are often fragmented, the available data are of varying quality and consistency and it is extremely difficult to efficiently bring information that is consistent and homogeneous together to carry out analyses and support decision making. The key issue is how to agree on the standards, technologies and techniques that are acceptable and then to encourage their collective implementation on a national basis.

2.3 The benefits of improved management and research capabilities

Increasing pressures on the available water resource for meeting demands in the different industry and community sectors requires continuing research into better understanding these demands, understanding the natural and artificial influences that affect the occurrence and distribution of water, and the development of tools to support decisions on how to best allocate and manage the resource.

2.4 The limitations of cloud seeding as a water resources management tool

The World Meteorological Organization (WMO) has maintained a critical expert review of the scientific basis and efficacy of artificial precipitation enhancement over the past thirty five years. Its most recent official statement on the Status of Weather Modification is at Attachment 2. This statement confirms that the ability to influence cloud microstructures has been demonstrated in the laboratory, simulated in numerical models, and verified through physical measurements in some natural systems such as fogs, layer clouds and cumulus clouds. However, on the basis of careful evaluation of rainfall enhancement experts around the world over the past 50 years, the WMO has found that direct physical evidence that precipitation, hail, lightning, or winds can be significantly modified by artificial means is limited.

A study undertaken by the Agriculture and Resource Management Council of Australian and New Zealand (ARMCANZ, 1995) concludes that there are only limited circumstances in which cloud seeding can be justified as an operational management investment. The report states that research has shown that, given appropriate conditions, cloud seeding can modify clouds and induce rain. However, the necessary favourable conditions occur relatively infrequently and the duration of the cloud seeding experiment necessary to demonstrate increased rainfall over a given area makes any experiment costly.

The report provides guidelines to be followed in order to ensure that any cloud seeding experiment has scientific credibility and has results that can be assessed objectively. A statistically designed experiment should be developed before any operational cloud seeding is undertaken. This is the only way that it can be determined if there has been any increase in rainfall from the experiment. Also care must be taken in that the impacts on the rainfall in the surrounding area will be uncertain.

2.5 The fundamental role of good observations and networks in the detection, monitoring and prediction of climate variability and change

Improving the ability of Australians to make better climate related decisions will require a continuation of the investment in domestic and international efforts to improve the collection and management of climate data. While Australia is currently striving to maintain its basic climatological observational systems at adequate levels, a major commitment will be required to ensure that the existing observation systems do not decline at a time when the information base they create is fundamental to sustainable resource development and management. The identification of a national Reference Climate Station network and a Global Climate

Observing System are vital initiatives in meeting Australia's future climate observation needs. It is noted however, that networks of finer scale are necessary for understanding climate and water resources variability at the river basin level.

2.6 The scientific basis for, and limitations of, weather and climate forecasting

The WMO (2002) has recently issued a statement on the scientific basis for, and limitations of, weather and climate forecasting (Attachment 3). This statement confirms the fundamental importance of the global observational data referred to in Section 2.5 above. The statement also points out that while scientific understanding of physical processes has made considerable progress through a variety of research activities, including field experiments, theoretical work, and numerical simulation, atmospheric processes are inherently non-linear, and not all physical processes can be understood or represented in Numerical Weather Prediction (NWP) models. Based on the current observed state of the atmosphere, weather prediction can provide detailed location and time-specific weather information on timescales of the order of two weeks. The grid scales used in these models mean however that they are currently of limited use in providing detailed forecasts of local weather such as cloud, fog and extremes such as intense precipitation and peak wind gusts. Some predictability of temperature and precipitation anomalies has been shown to exist at longer lead times out to a few seasons. This comes about because of interactions between the atmosphere, the oceans, and the land surface, which become important at seasonal time scales. The statement concludes by pointing out that skill in weather forecasting has advanced substantially since the middle of the twentieth century but that each component within the science and technology of weather forecasting and climate projection has its own uncertainties.

2.7 The status of climate forecast verification, and the need to undertake rigorous forecast assessment prior to the adoption of new systems

An important element of both weather and climate forecasting is that of verification of the forecast. Based on the verification studies completed to date, the Bureau of Meteorology Seasonal Climate Outlook scheme is comparable in skill to the range of other seasonal outlook schemes produced by other international agencies, both for rainfall and temperature. Furthermore, current research-based dynamical models (which use complex mathematical descriptions of the physical process governing the behaviour of the atmosphere and oceans) are yet to show a significant improvement over forecasts generated by statistical models such as that used in the Seasonal Climate Outlook. However, it is hoped that further research, by the Bureau of Meteorology, CSIRO and other research organisations, will progress such models to the stage when they will outperform current schemes and be adapted into operations.

2.8 The current Bureau of Meteorology public good forecasting and outlook services - strengths, weaknesses, and scope for improvement.

The very significant progress which has been made over the past two decades in the understanding of climate processes as a result of publicly funded Australian and international research suggests considerable basis for optimism in climate forecasting. In particular, advanced climate models currently being developed in the Bureau of Meteorology in collaboration with CSIRO and a number of overseas regional organisations offer the prospect of more skilful, diverse, and longer range forecasts. This impending move from statistically to dynamically based forecast systems marks an important step forward in climate prediction, but also presents renewed challenges. These new systems are among the computationally most expensive models to run, meaning investment in high end computing is a necessity. At the same time, the dynamical models are explicitly based on fundamental physical laws, and are, in effect, full computer models of the real world. Climate forecasting might also be expected to improve as applied and strategic research in such areas as decadal climate variability and natural and anthropogenic climate change are operationalised.

2.9 Determination of the precise nature of the weather forecast services required to optimise water usage, including specialist applications such as cloud seeding operations

Existing public interest weather forecast services provided by the Bureau already take into account the broad needs of Australia's rural industries and communities. There is a long history of collaboration and consultation, for example, with State agencies responsible for agriculture and land management, with industry bodies such as the national and state Farmers' Federations, with universities and other research bodies, and so on. The Bureau has recently placed a priority on hosting Regional Agricultural Services Consultative Committees to assist in the determination of future service needs.

However there has not been a systematic and specific analysis of Australia's weather service needs in relation to supporting optimum use of water on time scales from less than one day up to 1 to 2 weeks ahead. It would be desirable for such an analysis to be undertaken to ensure the Bureau's public interest efforts in this area are well targeted.

Notwithstanding the need for a systematic and specific analysis, it is possible to list some information requirements most likely to be relevant to water use decisions:

- Actual weather conditions: cumulative rainfall (over various time periods and comparisons with normal), evaporation, river heights, temperature (current value, hourly values, daily maximum and minimum), dewpoint and relative humidity, wind (speed, gusts, direction, wind run), cloud/sunshine/solar radiation amounts, atmospheric pressure;
- Forecast weather conditions: all of the above including rainfall likelihood and quantities (for periods ranging from hours to 1 to 2 weeks), access to current radar and satellite images to help judge likely rain events in the short term (minutes to hours).

2.10 Determination of whether such services can be provided operationally and accurately

Many of the services needed to optimise water usage are already provided operationally by the Bureau as part of its basic service in the public interest. Some services are not, particularly quantitative detail, some weather elements, and time periods more than one or two days ahead. Some services are available to private clients from commercial meteorological service providers including the Bureau's own commercial Special Services Unit.

A significant area of potential service enhancement would be for the Bureau to provide more detail in forecasts of rainfall. At present the Bureau uses descriptive words to characterise the expected rainfall (for example, light, heavy, etc.). Since such words require human interpretation (and are sometimes ambiguous or incomplete) it may be useful to accompany or replace them using numbers to specify time of occurrence, rainfall amount, and associated probabilities or uncertainties.

To provide more detailed rainfall forecasts, other weather elements, and longer time period outlooks would only be feasible operationally if accurate guidance were available from NWP models and associated statistical post-processing systems. Hence a key aspect of this issue is whether NWP and/or statistical systems provide the information required and whether it is accurate.

3. RESPONSES TO THE TERMS OF REFERENCE OF THE INQUIRY

Further supporting information on the considerations and issues summarised above is provided in terms of their specific relevant to the Terms of Reference of the Inquiry.

3.1 The role of the Commonwealth in ensuring adequate and sustainable supply of water in rural and regional Australia

Neither surface water nor groundwater are confined by State borders and increasingly issues of water quality, water availability and water resource development are having to be addressed at the broad regional and national level. The increasing disaggregation (bordering on fragmentation) of the public component of the water industry as a result of the corporatisation/privatisation under the COAG water reform process, has resulted in a reduced capability to manage water resources at these larger scales and has led to a reduction in the coordination and quality of important underpinning activities such as long-term data collection that are essential to this process.

There is an increasing need for the Commonwealth to take a lead facilitating and coordinating role here to address some of the gaps that are developing and to ensure that important regional and national objectives of sustainability are met.

This facilitation and coordination role needs to operate at both the regulatory policy level and at the technical management level. The new Natural Resource Management (NRM) Ministerial Council structure goes some way towards meeting the policy requirements that, in the more distant past, were met through the mechanisms of the former Australian Water Resource Council (AWRC). However, at the technical management level there is now a void. The experience from the National Land and Water Resources Audit (NLWRA) has been that there are serious deficiencies at this level that hampered the work of the Audit and reduced the usefulness of the information prepared by the Audit. Many of these deficiencies are a result of the lack of coordination between agencies, use of different standards, different interpretations of standards, the use of different techniques and technologies in data analysis and preparation and presentation of information. The Commonwealth could address these deficiencies by putting in place and then fostering the development of a collaborative structure through which the agencies responsible for water resource management can agree on, and then implement, solutions.

It will only be through the implementation of such a collaborative structure that a clear, consistent and comparable understanding of all of the country's water resources will emerge. This will enable regulatory and management practices to be implemented that will ensure that appropriate development can be undertaken and that sustainable water supplies will be available for rural and regional Australia.

The Commonwealth has an important role in ensuring an adequate and sustainable supply of water in rural and regional Australia through its (the Commonwealth's) activities in water resources assessment. Through the Bureau of Meteorology, the Commonwealth presently contributes to the improved assessment and management of rural water resources in the following ways.

- *Rainfall Networks*
  The official rainfall and evaporation networks of the Commonwealth Bureau of Meteorology are a key input to water resources assessment. In collaboration with the State and Territory water agencies, river basins in which there is a lack of rainfall data for adequate resource assessment have been identified. Many of these river basins are in the west and across the north of the country and include possible areas of development in the future. River basins in agricultural regions, in which there was insufficient data available for monitoring drought, have also been identified. A program to install additional rainfall stations in these river basins has been undertaken over the last 5 years resulting in excess of 200 stations either being installed or upgraded with the provision of additional equipment or communications links. While it can be difficult to find suitable monitoring sites in the more remote basins, the program continues as part of the normal Bureau network development activity.

- *Decision-Support Tools*
  The Bureau has contributed to the development of tools that can improve the management of water resources in a variable climate. These tools include objective analyses of the impacts of climate variability (including especially variability associated with the El Niño-Southern Oscillation (ENSO) phenomenon) on rainfall and streamflow to enable water managers to include objective analyses of these impacts of climate variability on their management decisions. These tools (RAINMAN and RAINMAN Streamflow) were developed under a Land and Water (Commonwealth) funded project lead by Queensland Department of Primary Industries, with the Bureau role being to provide a national source of rainfall and streamflow data. Further information on forecasting is provided in Section 3.5 (response to Term of Reference number 5) and Section 4 (on the Bureau's Services (current and future)).

- *Information Distribution (catalogues)*
  One of the consequences of the increasing fragmentation of water management organization is the difficulty of locating water resource data and information. This is particularly so for the public, organisations, researchers, government departments and consultants that are interested in data and information from a number of regions and/or States and Territories. To address this issue, the Bureau has assembled sets of metadata (data about data) that detail the river and rainfall monitoring networks in Australia and the contact details of the agencies where data and other details for these stations may be

obtained. This information is made available on the Bureau of Meteorology web site as databases that may be searched according to a range of user entered search criteria (http://www.bom.gov.au/hydro/wr). The further development of these types of products and their ongoing maintenance are some of the issues that a Commonwealth facilitated collaborative structure for water issues should address.

- *Stochastic Streamflow Generation*
  As a partner of the Cooperative Research Centre for Catchment Hydrology, the Bureau of Meteorology is involved in a project to develop stochastic rainfall and streamflow generation techniques applicable to Australia data sets. The use of stochastically generated time series of hydrological variables (such as rainfall and streamflow) should enable the design of rural water supply systems that correctly allows for water resource/climate variability. However, these techniques usually do not include trend information and thus their use under conditions of climate change need to be carefully considered. As part of a new CRC project to be undertaken in conjunction with CSIRO it is proposed to investigate the inclusion of climate change trends in these stochastic data generation techniques.

3.2 Commonwealth policies and programs in rural and regional Australia that could underpin stability of storage and supply of water for domestic consumption and other purposes

This Term of Reference addresses issues that are largely outside the role and functions of the Bureau of Meteorology. However, in announcing the inquiry, the House Agriculture, Fisheries and Forestry Committee Chair stated that "one issue we (the inquiry) will have to look at is the feasibility of cloud seeding, to alleviate drought conditions, such as rural Australia is now experiencing". The Bureau of Meteorology as the National Meteorological Authority and by virtue both of its own research program and its responsibility for Australian involvement with the programs and activities of the World Meteorology Organization has access to a wide range of information on cloud seeding which may be relevant to the inquiry.

On a regular basis, the World Meteorological Organization (WMO) holds international workshops and conferences on weather modification, including cloud seeding and also produces expert reviews of the status of weather modification, which are considered and endorsed by the WMO Executive Council. The most recent workshop was held in Mazatlán, Mexico in December 1999 (WMO/TD No. 1006, December 1999) and the most recent WMO Statement on the Status of Weather Modification was issued in June 2000.

The purpose of the workshop was to review three recent rain enhancement projects utilizing hygroscopic seeding techniques that had claimed positive rainfall increases from seeding, and that had supporting statistical evidence. The reported results dealt with single-cloud experiments, it was yet to be demonstrated that cost-beneficial increases in rain could be achieved on an area-wide basis.

The workshop concluded that the results of the three experiments were indeed exciting, and the topic sufficiently important, that additional work to understand the physical processes should be undertaken.

The WMO Statement (Attachment 2), endorsed by the Fifty-second Session of WMO Executive Council, states:

> "To answer the need for more water and less hail in many regions of the world, some progress has been made during the past ten years in the science and technology of

weather modification. Large numbers of programmes in fog dispersion, rain, snow enhancement and hail suppression are in operation. Several research experimental programmes are supported in some countries and include randomized statistical evaluations. Improved observational facilities, computer capabilities, numerical models, and understanding now permit more detailed examination of clouds and precipitation processes than ever before, and significant advances are consequently possible. New technologies and methods are starting to be applied and will help to lead to further understanding and development in this field.

In the light of this review of the status of weather modification, the following recommendations are made to interested Members of WMO:

(a) Cloud, fog and precipitation climatologies should be established in all countries as vital information for weather modification and water resource studies and operations;

(b) Operational cloud-seeding projects should be strengthened by allowing an independent evaluation of the results of seeding. This should include measurements of physical response variables and a randomized statistical component;

(c) Education and training in cloud physics, cloud chemistry, and other associated sciences should be an essential component of weather modification projects. Where the necessary capacity does not exist advantage should be taken of facilities in other Members;

(d) It is essential that basic measurements to support and evaluate the seeding material and seeding hypothesis proposed for any weather modification experiments be conducted before and during the project;

(e) Weather modification programmes are encouraged to utilize new observational tools and numerical modelling capabilities in the design, guidance and evaluations of field projects. While some Members may not have access or resources to implement these technologies, collaboration between member states (e.g. multinational field programmes, independent expert evaluations, education, etc.) are encouraged that could provide the necessary resources for implementing these technologies."

In November 1995, the Sub-Committee on Water Resources of the Sustainable Land and Water Resources Management Committee of the Agriculture and Resource Management Council of Australia and New Zealand published a set of guidelines for the utilisation of cloud seeding as a tool for water management in Australia. This Occasional Paper provided an outline of Australian experience and principles for water managers.

The paper concludes that there are only limited circumstances in which cloud seeding can be justified as an operational management investment. It states that research has shown that, given appropriate conditions, cloud seeding can modify clouds and induce rain. However, the necessary favourable conditions occur relatively infrequently and the duration of the cloud seeding experiment necessary to demonstrate increased rainfall over a given area makes any experiment costly.

The paper provides guidelines to be followed in order to ensure that any cloud seeding experiment has scientific credibility and has results that can be assessed objectively. A statistically designed experiment should be developed before any operational cloud seeding is undertaken. This is the only way that it can be determined if there has been any increase in rainfall from the experiment. Also, as indicated above, care must be taken in that the impacts on the rainfall in the surrounding area will be uncertain.

3.3 The effect of Commonwealth policies and programs on current and future water use in rural Australia

This Term of Reference relates to the issue of water use and is thus outside the role and functions of the Bureau of Meteorology.

3.4 Commonwealth policies and programs that could address and balance the competing demands on water resources

This Term of Reference relates to the issue of water use and is thus outside the role and functions of the Bureau of Meteorology.

3.5 The adequacy of scientific research on the approaches required for adaptation to climate variability and better weather prediction, including the reliability of forecasting systems and capacity to provide specialist forecasts

In June 2002, the Fifty-fourth Session of the WMO Executive Council issued a WMO Statement on the Scientific Basis for, and Limitations of, Weather and Climate Forecasting. This statement recognises the importance of the cooperation of countries under the WMO World Weather Watch in the provision of the basic global observational data that are essential to describe the current (initial) state of the atmosphere, the role of numerical models in representing the physical and dynamical processes governing the behaviour of the atmosphere and ocean, the combination of these activities in a coordinated, international manner to prepare forecasts and warnings and the ability to monitor extreme events in real-time and to issue warnings using increasingly sophisticated equipment (for example, radars and satellites).

The statement concludes that the skill in weather forecasting has advanced substantially since the middle of the twentieth century, largely supported by the advancement of computing, observation (radar and satellite, in particular), and telecommunications systems, and the development of numerical weather prediction models along with the associated data-assimilation techniques. This has been greatly facilitated because of the vast experience of both forecasters and decision-makers in producing and using forecast products. Nevertheless, each component within the science and technology of weather forecasting and climate prediction has its own uncertainties. Some of these are associated with a lack of a complete understanding of, or an inherent limitation of the predictability of, highly complex processes. Others are linked still to the need for further advances in observing or computing technology, or an inadequate transfer between research and operations. Finally, one cannot under-estimate the importance of properly communicated weather forecasts to well-educated users.

Without doubt, significant benefits will result from continued attention to scientific research and the transfer of knowledge gained from this work into the practice of forecasting. Furthermore, a recognition of the limitations of weather and climate forecasting, and when possible an estimate of the degree of uncertainty, will result in the improved use of forecasts and other weather information by decision-makers. Ultimately the objective is for the scientific and user communities to work better together, realizing even greater benefits.

Any strategies for adaptation to future climate change will require a sound understanding of past and present climate variability. This can only be achieved with a secure, stable and reliable observation network, both within Australia and globally. Understanding Australian rainfall variability is dependent on data collected throughout the globe – at the surface, in the atmosphere, and in the sub-surface ocean.

The validation and refinement of numerical climate models depends on high quality observations of the "real" climate, both past and present. However, serious concern exists about the adequacy of current global observation networks to meet such needs. In recent decades, there has been a general decline in the numbers of observation stations worldwide. In addition, automated observation systems, whilst providing faster access and more frequent data, have placed additional strain on traditional data management and quality checking procedures. With a network of hundreds of professional, co-operative and volunteer weather observers, augmented by a network of Automatic Weather Stations, the Bureau of Meteorology collects, checks and archives Australia's instrumental rainfall record. Analyses of changes within this record are complicated by non-climatic discontinuities caused by changes in station location, exposure, instrumentation and observation practice. Only about 270 of the many thousands of individual rainfall records within Australia are long enough, and are of sufficient quality, for the examination of long-term rainfall trends.

An annual mean average of Australia's high-quality rainfall records suggests a weak increase in mean rainfall over the twentieth century (Figure 1). However, this trend is dominated by large year-to-year variations, partly due to the El Niño-Southern Oscillation. Long-term trends are not uniform throughout the country (Figure 2). The strongest rise in rainfall over the past century has been observed in the northern tropics. Conversely, isolated parts of southeast Queensland and the south of the country show a decline in rainfall. The decline in far southwest Western Australia is of great concern to farmers in the region. Improving the ability of Australians to make better climate related decisions will require investment in domestic and international efforts to improve the collection and management of climate data. An urgent commitment is required to halt and reverse the decline of existing observation systems. The establishment of a national Reference Climate Station network and a Global Climate Observing System (GCOS) are vital initiatives in meeting Australia's future climate observation needs.

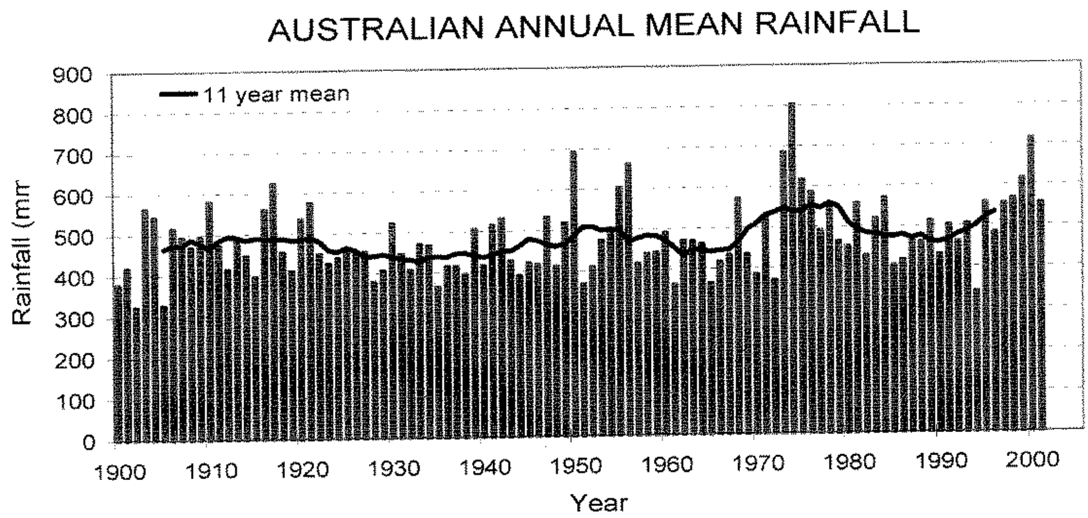


Figure 1. Australian annual mean rainfall (mm) since 1900.

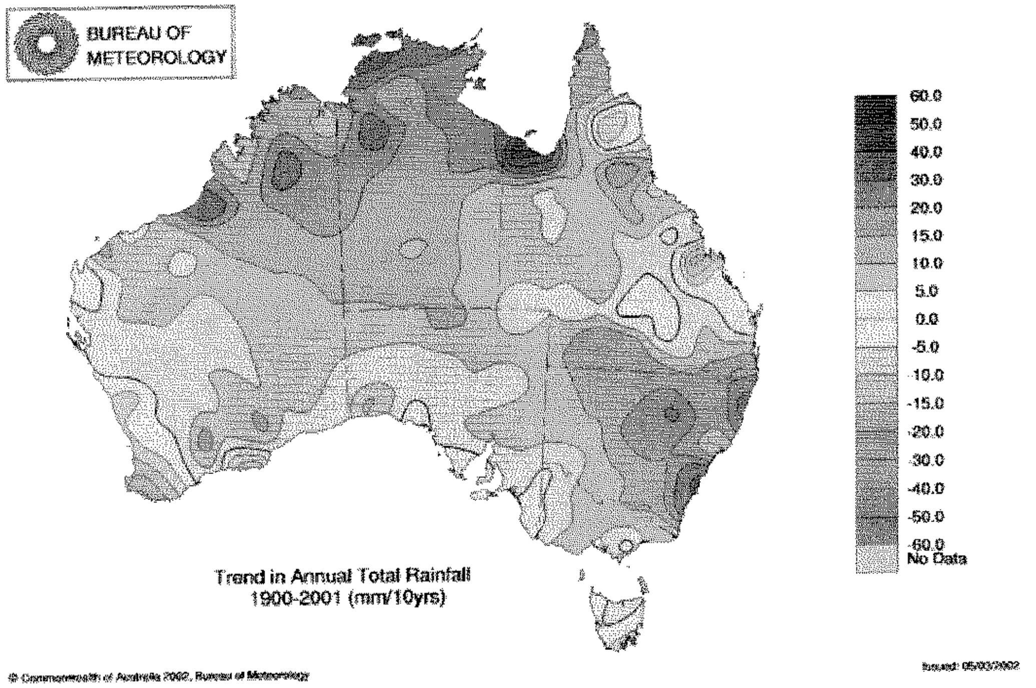


Figure 2. Trend in annual total rainfall (in mm/decades) across Australia (1900-2001).

The reliability of the Bureau of Meteorology's operational Seasonal Climate Outlook scheme in forecasting the seasonal shifts from normal of both rainfall and temperature has been examined closely at the Bureau of Meteorology's National Climate Centre. The need for such an examination, in terms understood by end users such as those in farming and agribusiness, was highlighted by a survey conducted by the SILO program; a Bureau of Meteorology (in conjunction with the AFFA Climate Variability in Agriculture R&D Program) project aimed at delivering specialist information to those on the land. This survey underlined the need for easily understood verification statistics if climate forecasts were to be used to their full potential. This was noted and action taken, with the production of web pages available to the general public showing detailed information on the skill of the outlooks produced by the Bureau of Meteorology (see: http://www.bom.gov.au/silo/products/verif/).

The Bureau of Meteorology's operational Seasonal Climate Outlook scheme was upgraded to its current format in the year 2000, and hence this model has only been producing, monthly outlooks for a little over 2 years. This is too short a time to determine the models skill directly. To test the models performance, it has been re-run on historical data spanning the 50 years from 1950 to 1999. From these 50 years, generating 12 outlooks per year (i.e. one per month), an assessment has been performed on the 600 forecasts available.

Outlooks were assessed using a simple "percentage consistent" (i.e., the percentage of outlooks that favoured the observed outcome of above or below median). This simple measure was compared with more rigorous and scientific assessments and shown to provide comparable general measures of skill whilst remaining comprehensible to the lay person.

Results, calculated over all months for the period 1950-1999 (i.e., all 600 hindcasts), show that the rainfall outlooks have greatest skill in the regions of Queensland and the Northern Territory (Fig. 3). Statistical testing suggests that these regions are likely to be skilful (i.e., broadly speaking, likely to be better than a person guessing). For the vast majority of the rest of Australia, the outlooks produced forecasts that, on average, were better than random guesses (red shading in Fig. 3). If the forecast scheme had no real skill, we might expect only 50% of the continent to be better than a guess, and 50% to be worse than a guess. Figure 3 clearly shows that the Seasonal Climate Outlook far exceeds this criterion. Even higher degrees of skill have been shown for the temperature outlooks.

The above results are averaged across all seasons. It is often far more useful for the end user to consider the skill for individual seasons when determining the worth of the Seasonal Climate Outlooks in their region. The above web page also provides information on a season by season basis. Furthermore, users may download the data for their own location which was used to produce the season by season forecasts, and make their own personal appraisal. The assessment of the outlooks for the period from September to November are shown in Figure 4. This shows that the spring outlooks provide greatest skill over much of the eastern half of Australia, with values in many locations well in excess of those shown in the average over all seasons (Figure 3). This, for instance, would be an important consideration to those examining spring rainfall in particular.

Whilst direct comparisons with other models are not possible (due to different periods over which models are assessed), general comparisons (also available via the above web page) suggest that the Bureau of Meteorology Seasonal Climate Outlook scheme is comparable to the skill of other seasonal outlook schemes produced by other agencies, both for rainfall and temperature. Furthermore, current research based dynamical models (which use complex mathematical descriptions of the behaviour of the atmosphere and oceans) are yet to show a significant improvement over forecasts generated by statistical models such as that used in the Seasonal Climate Outlook. However it is hoped that further research, in the Bureau of Meteorology, CSIRO and other research organisations, will progress such models to the stage when they will outperform current schemes and be adapted into operations.

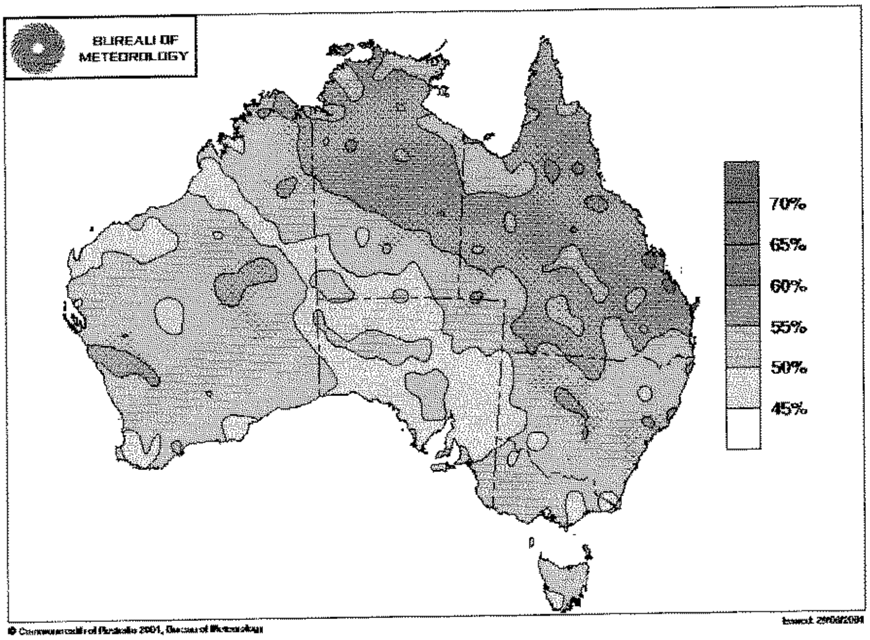


Figure 3. Percentage of outlooks consistent with the observed rainfall (above/below median), calculated over all seasons from 1950-1999. Stippling on this plot shows regions that are statistically most skilful when averaged across all seasons. Some regions may have higher or lower values during individual seasons.

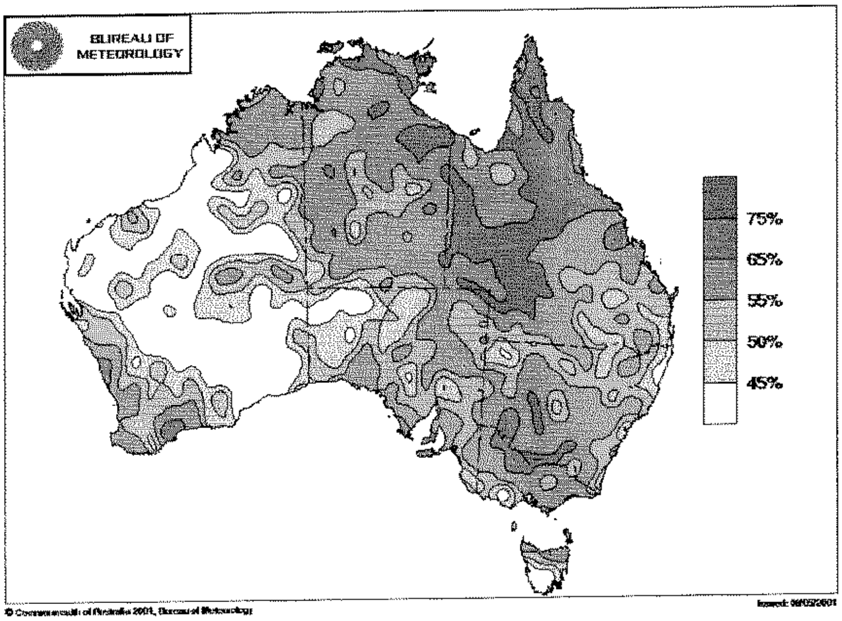


Figure 4. Percentage of outlooks consistent with the observed rainfall (above/below median), calculated over all spring (Sept-Nov) seasons from 1950-1999.

Since 1989 the Bureau of Meteorology, as part of its Climate Monitoring Service, has provided a range of climate forecast products to the Australian public. Based on the best available science from the Bureau of Meteorology, CSIRO, and elsewhere, this service has been progressively upgraded over the past decade.

The present service, provided to the general public and a wide range of key interest groups including rural producers, water managers, and emergency service agencies is provided in the public interest as part of the Bureau of Meteorology basic service. More specialised forecasts based on this forecast system are provided, on a request basis, to individual customers (particularly energy distributors) by the Bureau of Meteorology Special Services Unit on a consultancy basis. Based on the best available science, the basic service provides probability based forecasts of the likelihood of rainfall and temperature (maximum, minimum, mean, and daily range) lying in one of three equal size categories (average, above average, and below average), as well as above/below the median. For temperature, maximum likelihood quantitative forecasts are also made, which give the most likely temperature anomaly for the forecast season. A similar product is under development for rainfall, with operational implementation expected within 18 months.

These forecasts use a newly developed non-linear forecast system which relates the variation of sea surface temperatures in the Indian and Pacific Oceans to Australian climate variability. The underlying system is generic in space, time and parameter, and has been adapted for climate prediction in other countries (e.g., Fiji and Vietnam), and to the prediction on monthly through annual time periods, with lead-times from zero to twelve months. The forecasts, which are produced operationally, are for a three-month period at one month lead time, so for example a winter forecast is produced early in May. The choice of forecast lead time and period reflect the fact that forecast accuracy tends to decline with increased lead-time and decreased prediction period, while longer forecast periods are likely to be less useful for rural production decision making.

The focus of this service on probabilistic forecasting reflects the fact that the ocean-atmosphere system is chaotic on longer time scales. Beyond approximately two weeks, small uncertainties in the structure of the atmosphere (even for a perfect model), grow so large that individual deterministic forecasts have little or no skill. At the same time, the role of the slowly varying ocean in biasing outcomes towards wetter or drier (for example) states lasts for months through to potentially years. This means that while individual atmospheric states are not predictable on climate scales, the underlying probability distribution of these states remains at least partially predictable. Under this paradigm, representation of seasonal forecasts should be through probabilities and, where appropriate, augmented with estimates of the most likely (or mid points) of the forecast distributions.

In summarising the adequacy of this service for use in the adaptation to climate variability (and change), it is important to distinguish between the adequacy as measured against user demands and expectation, and that which might be possible given current or near-future scientific knowledge. Research undertaken by the Bureau of Meteorology has revealed the underlying forecast systems to be significantly skilled over most parts of Australia. This is particularly true for temperature, and to a lesser extent precipitation. At the same time, the potential for increased volatility in outcomes through proactive management dictates careful risk assessment. Further, the probabilistic nature of forecasts, as dictated by the chaotic nature of climate, means that benefit in the use of forecasts should be measured over a period of years.

As part of its operational service, the Bureau of Meteorology has strong ties to a range of public and private sector organisations and individuals who are sensitive to climate variability and change, and/or who could benefit from improved risk management through the use of climate predictions. These relationships with groups such as New South Wales Department of Agriculture, Agriculture Western Australia, and The Kondinin Group, are seen as mutually beneficial, in so far as the Bureau of Meteorology service benefits and improves. These activities include a range of formal and informal meeting groups, and recently included a major conference facilitated through the Climate Variability in Agriculture Program of the Land and Water Resources Research and Development Cooperation (LWRRDC). It is fair to summarise the key client desire is for both increased forecast skill and increased forecast lead-time, suggesting a degree of inadequacy from a client's perspective.

In terms of forecast performance, the operational service necessarily lags the science, owing to the need for careful and rigorous assessment of advances in the science prior to operational implementation. As previously discussed, the forecast system has a level of skill which is comparable or better than that achievable by other rigorous forecast systems, and is in all likelihood not significantly below that which is achievable given the present state of the underlying science. However, theoretical results from a range of conceptual and physically based models suggest that their remains considerable future scope for forecast improvement.

The very significant progress which has been made in the past decade in climate prediction as a result of publicly funded Australian and international research suggests considerable reason for optimism in climate forecasting. In particular, advanced climate models currently being developed in the Bureau of Meteorology in collaboration with CSIRO Marine Research offer the prospect of more skilful, diverse, and longer range forecasts. This impending move from statistically to dynamically based forecast systems represents a significant milestone in climate prediction, but also presents renewed challenges. These new systems are among the computationally most expensive models to run, meaning investment in high end computing is a necessity. At the same time, the dynamical models are explicitly based on fundamental physical laws, and are, in effect, full computer models of the real world. Climate forecasting might also be expected to improve as applied and strategic research in such areas as decadal climate variability and natural and anthropogenic climate change are operationalised.

4. BUREAU OF METEOROLOGY SERVICES – CURRENT AND FUTURE

4.1 Current services

Current Bureau of Meteorology services fall into two categories; provision of (a) observational data and (b) forecasts of relevant weather elements:

(a) Observational Data

Relevant observational data are currently provided in a variety of bulletins, viz
- 1-3 rainfall bulletins (mainly flood warning stations)
- Daily rainfall bulletins
- Weekly rainfall bulletins
- Monthly rainfall bulletins
- Daily weather bulletins
- Current observations bulletins
- River height bulletins (hourly and daily)

The weather elements included in these bulletins include:
- Daily maximum temperature
- Daily minimum temperature

- Current temperature
- Relative humidity
- Dewpoint
- Cumulative rainfall
- Wind speed, direction and gust strength
- Cloud amount
- Atmospheric pressure

The Bureau operates an extensive network of observation stations. There are approximately 800 stations monitoring most of the above observation types and approximately 7000 stations observing rainfall. Frequency of observation intervals rages from 1 minute for many automatic weather stations through hourly, daily, monthly and annual. Networks have also been established for the collection of observations in the upper atmosphere, including solar radiation and atmospheric composition. Observations are also made from ships, drifting buoys, tide gauges and other instruments which are critical for monitoring the ocean.

Access to much of this data is available freely through the Bureau's Internet site and special purpose users can gain access to additional information through subscription services.

Development work is now well advanced to provide near real time access to other observational data including soil temperatures, wind run and pan evaporation which could further enhance the decision making processes of major water users such as irrigators in the agricultural sector.

Additionally, visible and infra-red satellite cloud imagery together with radar reflectivity images are provided in real time.

There is scope to evaluate these services specifically from the perspective of supporting water use decisions as to whether they provide relevant detail and spatial coverage.

(b) Weather Forecasts

Currently quantitative forecasts of daily maximum and minimum temperatures are issued for major provincial centres for forecast periods up to four days.

Rainfall forecasts are provided in descriptive words for provincial cities and for weather forecast districts across Australia. The words used give some but not a fully detailed indication of timing, amount, and likelihood. Other weather elements that are described to some extent using words are wind speed and direction, and amount of cloud and sunshine.

Evaluation of these weather forecasts is incomplete. There is adequate evaluation of the accuracy of numerical forecasts (daily maximum and minimum temperatures) - the case study below describes the typical accuracy analysis for a selection of rural centres. However, evaluation of the accuracy of forecasts conveyed in descriptive words is difficult and is currently done in a subjective fashion. There is scope to improve the evaluation of the accuracy of these services and whether they suit the needs of water use decisions.

Case Study: annual accuracy analysis for next-day maximum and minimum temperature forecasts, for a selection of rural centres around Australia:

Typical Annual next-day Temperature Forecast Accuracy (degrees C)				
Station	Maximum		Minimum	
	Bias	RMSE*	Bias	RMSE
Launceston	-0.2	1.8	-0.2	2.2
Shepparton	-0.2	1.9	-0.1	2.2
Parkes	-0.3	2.0	-0.1	2.5
Charleville	0.2	2.3	0.2	2.4
Tennant Creek	-0.1	2.2	-0.2	2.0
Geraldton	-0.2	2.0	-0.1	2.4
Renmark	-0.4	2.3	-0.5	2.1

* RMSE = root mean squared error

4.2 Future services

The priority for provision of additional weather forecasting services is the determined assessment of the general community benefit to be gained from such services coupled with the need to be able to scientifically demonstrate sufficient accuracy. Likely areas of benefit are (a) more detailed rainfall forecasts, (b) more detailed forecasts of other weather elements, and (c) longer time period outlooks.

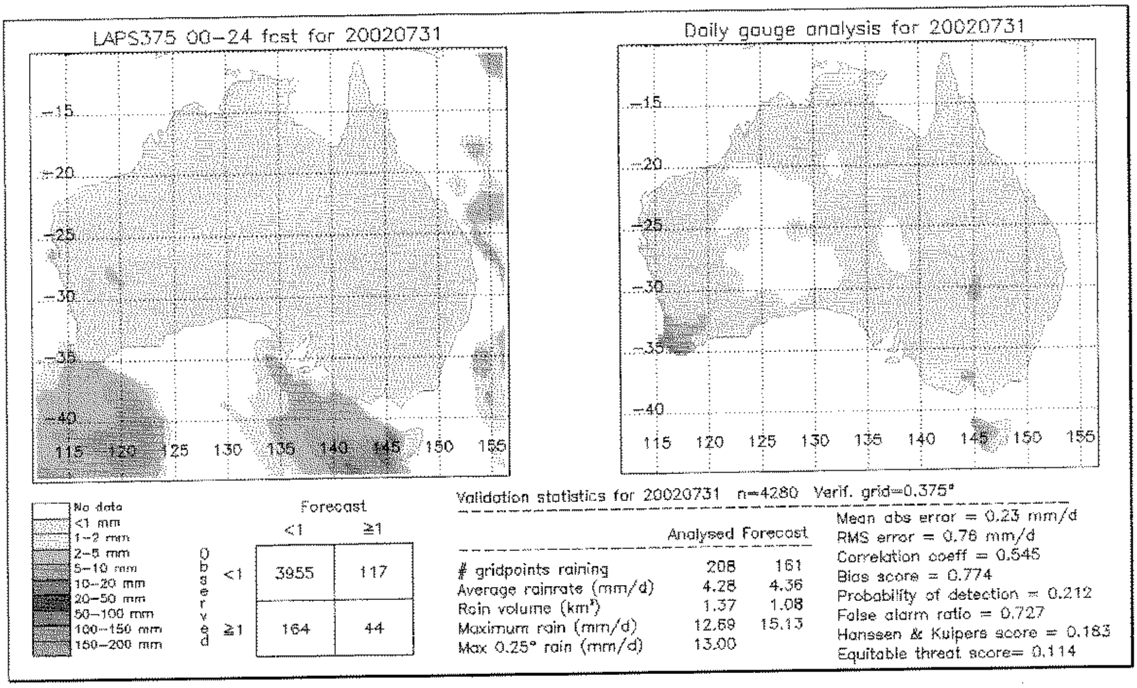
(a) more detailed rainfall forecasts

The Bureau has been actively investigating the potential skill it could display if it were to provide quantitative rainfall forecasts (that is rainfall amounts in millimetres rather than the terms light, heavy, intermittent and so on used now).

Forecast decisions rely heavily on the guidance provided by Numerical Weather Predication (NWP) models. Detailed investigation of the performance of NWP models in predicting rainfall amounts is underway (Figure 5).

Forecast decisions have also been made in trial mode for state and territory capital cities for the next day. These consist of both categorical rain/no rain forecasts together with forecasts of the likely quantitative range within which the following day's rainfall will fall, using ranges shown below:

Rainfall Range	Precipitation Amount (mm)
0	No precipitation
1	0.2 – 2.4
2	2.5 – 4.9
3	5.0 – 9.9
4	10.0 – 19.9
5	20.0 – 39.9
6	40.0 – 79.9
7	80.0 and above



		Forecast	
		<1	≥1
Observed	<1	3955	117
	≥1	164	44

Validation statistics for 20020731 n=4280 Verif. grid=0.375°

	Analysed	Forecast
# gridpoints raining	208	161
Average rainrate (mm/d)	4.28	4.36
Rain volume (km^3)	1.37	1.08
Maximum rain (mm/d)	12.69	15.13
Max 0.25° rain (mm/d)	13.00	

Mean abs error = 0.23 mm/d
RMS error = 0.76 mm/d
Correlation coeff = 0.545
Bias score = 0.774
Probability of detection = 0.212
False alarm ratio = 0.727
Hanssen & Kuipers score = 0.183
Equitable threat score= 0.114

Figure 5. Example of an investigation of the performance of the LAPS NWP model in predicting rainfall amounts.

Recent performance is shown in the table below. It shows the percentage of categorical rain/no rain forecasts for the next day that were correct, the percentage of quantitative forecasts which identified the correct range, the percentage which fell within one range and the percentage of forecasts which were in error by more than three ranges.

Latest Annual Rainfall Forecast Performance				
	Rain/no rain	Within fcst range	Within 1 range	Error > 3 ranges
Hobart	73.1	53.5	33.5	0.3
Melbourne	78.9	53.8	34.2	0.9
Sydney	75.1	46.5	32.5	0.9
Brisbane	77.5	57.3	25.4	0.9
Darwin	78.9	54.8	16.4	6.2
Perth	79.2	60.4	27.1	0.0
Adelaide	81.4	63.5	28.7	0.0

A decision on whether, and at what stage (in terms of demonstrable forecast skills), to provide quantitative rainfall forecasts to the community at large has not been made.

Another aspect of rainfall forecasts that could be provided in greater detail is the likelihood of occurrence. At present descriptive terms are sometimes used (such as "chance of") except for Canberra where an actual percentage probability of rain is provided (such as "20 per cent probability of rain"). Current developments in "ensemble" NWP models offer the promise of providing useful guidance to support such detailed specification of likelihood.

Further investigation would be required to establish the accuracy that could be achieved across Australia as well as the benefits of such detail to water use decisions.

(b) more detailed forecasts of other weather elements

As with rainfall, it may be that more detailed forecasts of other weather elements (wind, evaporation, dewpoint and relative humidity, cloud/sunshine/solar radiation amounts, etc) would assist water use decisions.

At present such comprehensive detail would be difficult to achieve. A major staff commitment is required through the fire seasons around Australia, for example, to provide detailed forecasts of wind, temperature and humidity to fire authorities to support accurate assessment of fire danger. However further development and investigation of the capabilities of NWP models may soon allow reliable detailed forecasts to be provided widely with much less call on staff resources.

(c) longer time period outlooks

Although experimental maximum temperature forecasts with lead times of 7 days now exhibit similar skill to that shown by 4 day forecasts when they were introduced in the 1970s, the most recent experimental study into quantitative rainfall forecasts suggested that there is little skill demonstrated by quantitative precipitation forecasts beyond three days. The table below shows the most recent available verifications. Again, the figures are the percentage of forecasts issued the previous day which are correct, in the case of categorical rain/no rain forecasts, the percentage of quantitative forecasts which are within the correct range, the percentage which are within one range and the percentage of forecasts which are in error by more than three ranges. These are compared to the comparable values obtained by "persistence" (a simple forecast that tomorrow will be the same as today – this provides a baseline against which to demonstrate skill).

Rainfall Forecast Performance for Melbourne, November 2000														
	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7	
	fcst	pers	fcst	pers	fcst	pers	fcst	pers	fcst	pers	fcst	pers	fcst	pers
Rain/no rain	71	69	72	69	62	69	76	69	65	69	62	69	65	69
Within fcst range	57	52	52	52	45	52	55	52	48	52	48	52	48	52
Within 1 range	32	28	31	28	41	28	31	28	28	28	35	28	35	28
Error > 3 ranges	4	3	0	3	0	3	0	3	0	3	0	3	0	3

Again, further development and investigation of the capabilities of NWP models will progressively allow reliable longer time period forecasts to be provided.

5. CONCLUSION

The submission has raised a number of issues of importance to future water supplies for Australia's rural industries and communities from the perspective of the national and international responsibilities of the Bureau of Meteorology for monitoring, research, and provision of meteorological and hydrological services. The Bureau would be pleased to expand on these issues and any related matters of interest to the House of Representatives Standing Committee on Agriculture, Fisheries and Forestry Inquiry into Future Water Supplies for Australia's Rural Industries and Communities.

ATTACHMENT 1

THE METEOROLOGY ACT 1955

METEOROLOGY

No. 6 of 1955.[1]

An Act relating to the Commonwealth Bureau of Meteorology.

[Assented to 23rd May, 1955]

[Date of Commencement, 20th June, 1955]

Be it enacted by the Queen's Most Excellent Majesty, the Senate, and the House of Representatives of the Commonwealth of Australia, as follows:

1. This Act may be cited as the *Meteorology Act* 1955. Short title

2. The *Meteorology Act* 1906 is repealed. Repeal

3. In this Act, unless the contrary intention appears - Definitions
"the Bureau" means the Commonwealth Bureau of Meteorology established by this Act;
"the Director" means the Director of Meteorology.

4.[1] This Act extends to all the Territories of the Commonwealth. Extension to Territories

5. (1) For the purposes of this Act, there shall be a Commonwealth Bureau of Meteorology and a Director of Meteorology. The Commonwealth Bureau of Meteorology

(2) The Bureau shall be under the charge of the Director of Meteorology, who shall, subject to the directions of the Minister, have the general administration of this Act.

6. (1) The functions of the Bureau are- Functions of the Bureau

(a) the taking and recording of meteorological observations the Bureau and other observations required for the purposes of meteorology;
(b) the forecasting of weather and of the state of the atmosphere;
(c) the issue of warnings of gales, storms and other weather conditions likely to endanger life or property, including weather conditions likely to give rise to floods or bush fires;
(d) the supply of meteorological information;
(e) the publication of meteorological reports and bulletins;
(f) the promotion of the use of meteorological information;
(g) the promotion of the advancement of meteorological science by means of meteorological research and investigation or otherwise;

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[1] Amended by No. 123 of 1973

(h) the furnishing of advice on meteorological matters; and

(i)[1] co-operation with the authority administering the meteorological service of any other country in relation to any of the matters specified in the preceding paragraphs of this sub-section.

(2) The Bureau shall perform its functions under this Act in the public interest generally and in particular-

(a) for the purposes of the Defence Force;

(b) for the purposes of navigation and shipping and of civil aviation; and

(c) for the purpose of assisting persons and authorities engaged in primary production, industry, trade and commerce.

Powers of Director

7. (1) The Director has such powers as are necessary to enable the Powers of Bureau to perform its functions under the last preceding the Director section, and, in particular, may-

(a) establish meteorological offices and observing stations;

(b) arrange with any Department, authority or person to take and record meteorological observations and transmit meteorological reports and information;

(c) arrange means of communication for the transmission and reception of meteorological reports and information; and

(d) arrange for the training of persons in meteorology.

(2)[2] The Departments and authorities with which, and the persons with whom, arrangements may be made under the last preceding sub-section include Departments and authorities of a State or Territory of the Commonwealth and persons in the service of such a State or Territory or of such a Department or authority.

Charges

8. The Director may, subject to any directions of the Minister, make charges for forecasts, information, advice, publications and other matter supplied in pursuance of this Act.

Regulations

9. The Governor-General may make regulations, not inconsistent Regulations with this Act, prescribing all matters which by this Act are required or permitted to be prescribed, or which are necessary or convenient to be prescribed for carrying out or giving effect to this Act.

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[2] Amended by No. 123 of 1973

ATTACHMENT 2

WMO STATEMENT ON THE STATUS OF WEATHER MODIFICATION

INTRODUCTION

For thousands of years people have sought to modify weather and climate so as to augment water resources and mitigate severe weather. The modern technology of weather modification was launched by the discovery in the late 1940s that supercooled cloud droplets could be converted to ice crystals by insertion of a cooling agent such as dry ice or an artificial ice nucleus such as silver iodide. Over 50 years of subsequent research have greatly enhanced our knowledge about the microphysics, dynamics and precipitation processes of natural clouds (rain, hail, snow) and the impacts of human interventions on those processes.

Currently, there are dozens of nations operating more than 100 weather modification projects, particularly in arid and semi-arid regions all over the world, where the lack of sufficient water resources limits their ability to meet food, fibre, and energy demands. The purpose of this document is to present a review of the status of weather modification.

The energy involved in weather systems is so large that it is impossible to artificially create rainstorms or to alter wind patterns to bring water vapour into a region. The most realistic approach to modifying weather is to take advantage of microphysical sensitivities wherein a relatively small human-induced disturbance in the system can substantially alter the natural evolution of atmospheric processes.

The ability to influence cloud microstructures has been demonstrated in the laboratory, simulated in numerical models, and verified through physical measurements in some natural systems such as fogs, layer clouds and cumulus clouds. However, direct physical evidence that precipitation, hail, lightning, or winds can be significantly modified by artificial means is limited. The complexity and variability of clouds result in great difficulties in understanding and detecting the effects of attempts to modify them artificially. As knowledge of cloud physics and statistics and their application to weather modification has increased, new assessment criteria have evolved for evaluating cloud-seeding experiments. The development of new equipment - such as aircraft platforms with microphysical and air-motion measuring systems, radar (including Doppler and polarization capability), satellites, microwave radiometers, wind profilers, automated raingauge networks, mesoscale network stations - has introduced a new dimension. Equally important are the advances in computer systems that permit large quantities of data to be processed. New data sets, used in conjunction with increasingly sophisticated numerical cloud models, help in testing various weather modification hypotheses. Chemical and chaff tracer studies help to identify airflow in and out of clouds and the source of ice or hygroscopic nucleation as the seeding agent. With some of these new facilities, a better climatology of clouds and precipitation can be prepared to test seeding hypotheses prior to the commencement of weather modification projects.

If one were able to predict precisely the precipitation from a cloud system, it would be a simple matter to detect the effect of artificial cloud seeding on that system. The expected effects of seeding, however, are almost always within the range of natural variability (low signal-to-noise ratio) and our ability to predict the natural behaviour is still limited.

Comparison of precipitation observed during seeded periods with that during historical periods presents problems because of climatic and other changes from one period to another, and therefore is not a reliable technique. This situation has been made even more difficult with the mounting evidence that climate change may lead to changes in global precipitation amounts as well as to spatial redistribution of precipitation.

In currently accepted evaluation practice, randomization methods (target/control, crossover or single area) are considered most reliable for detecting cloud-seeding effects. Such randomized tests require a number of cases readily calculated on the basis of the natural variability of the

precipitation and the magnitude of the expected effect. In the case of very low signal-to-noise ratios, experiment durations in the range of five to over ten years may be required. Whenever a statistical evaluation is required to establish that a significant change resulted from a given seeding activity, it must be accompanied by a physical evaluation to:

1. Confirm that the statistically observed change is likely due to the seeding; and

2. Determine the capabilities of the seeding method to produce desired effects under various conditions.

The effect of natural precipitation variability on the required length of an experiment can be reduced through the employment of physical predictors, which are effective in direct proportion to our understanding of the phenomenon. The search for physical predictors, therefore, holds a high priority in weather modification research. Physical predictors may consist of meteorological parameters (such as stability, wind directions, pressure gradients) or cloud quantities (such as liquid water content, updraught speeds, concentrations of large drops, ice-crystal concentration or radar reflectivity).

Objective measurement techniques of precipitation quantities are to be preferred for testing weather modification methods. These include both direct ground measurements (e.g. rain gages and hail pads) and remote sensing techniques (e.g. radar, satellite). Secondary sources, such as insurance data (as have in the past been employed to show changes in hail intensity) are, at least by themselves, not held to be satisfactory in most situations.

Operational programmes should be conducted with recognition of the risks inherent in a technology which is not totally developed. For example, it should not be ignored that, under certain conditions, seeding may cause more hail or reduce precipitation. However, properly designed and conducted operational projects seek to detect and minimize such adverse effects. Therefore, weather modification managers are encouraged to add scientifically accepted evaluation methodologies to be undertaken by experts independent of the operators.

Brief summaries of the current status of weather modification are given in the following sections. These summaries were restricted to weather modification activities that appear to be based on acceptable physical principles and which have been tested in the field.

FOG DISPERSAL

Different techniques are being used to disperse warm (i.e. at temperatures greater than 0°C) and cold fogs. The relative occurrence of warm and cold fogs is geographically and seasonally dependent.

The thermal technique, which employs intense heat sources (such as jet engines) to warm the air directly and evaporate the fog has been shown to be effective for short periods for dispersal of some types of warm fogs. These systems are expensive to install and to use. Another technique that has been used is to promote entrainment of dry air into the fog by the use of hovering helicopters or ground based engines. These techniques are also expensive for routine use.

To clear warm fogs, seeding with hygroscopic materials has also been attempted. An increase in visibility is sometimes observed in such experiments, but the manner and location of the seeding and the size distribution of seeding material are critical and difficult to specify. In practice the technique is seldom as effective as models suggest. Only hygroscopic agents should be used that pose no environmental and health problems.

Cold (supercooled) fog can be dissipated by growth and sedimentation of ice crystals. This may be induced with high reliability by seeding the fog with artificial ice nuclei from ground-based or airborne systems. This technique is in operational use at several airports and highways where there is a relatively high incidence of supercooled fog. Suitable techniques are dependent upon wind, temperature and other factors. Dry ice has commonly been used in airborne systems. Other systems employ rapid expansion of compressed gas to cool the air enough to form ice crystals. For example, at a few airports and highway locations, liquid nitrogen or carbon dioxide is being used in ground-based systems. A new technique, which has been demonstrated in limited trials, makes use of dry ice blasting to create ice crystals and promote rapid mixing within the fog. Because the effects of this type of seeding are easily measured and results highly predictable, randomized statistical verification generally has been considered unnecessary.

PRECIPITATION (RAIN AND SNOW) ENHANCEMENT

This section deals with those precipitation enhancement techniques that have a scientific basis and that have been the subject of research. Other non-scientific and unproven techniques that are presented from time to time should be treated with the required suspicion and caution.

Orographic mixed-phase cloud systems

In our present state of knowledge, it is considered that the glaciogenic seeding of clouds formed by air flowing over mountains offers the best prospects for increasing precipitation in an economically viable manner. These types of clouds attracted great interest in their modification because of their potential in terms of water management, i.e. the possibility of storing water in reservoirs or in the snowpack at higher elevations. There is statistical evidence that, under certain conditions, precipitation from supercooled orographic clouds can be increased with existing techniques. Statistical analyses of surface precipitation records from some long-term projects indicate that seasonal increases have been realized.

Physical studies using new observational tools and supported by numerical modelling indicate that supercooled liquid water exists in amounts sufficient to produce the observed precipitation increases and could be tapped if proper seeding technologies were applied. The processes culminating in increased precipitation have also been directly observed during seeding experiments conducted over limited spatial and temporal domains. While such observations further support the results of statistical analyses, they have to date been of limited scope. The cause and effect relationships have not been fully documented, and thus the economic impact of the increases cannot be assessed.

This does not imply that the problem of precipitation enhancement in such situations is solved. Much work remains to be done to strengthen the results and produce stronger statistical and physical evidence that the increases occurred over the target area and over a prolonged period of time, as well as to search for the existence of any extra-area effects. Existing methods should be improved in the identification of seeding opportunities and the times and situations in which it is not advisable to seed, thus optimizing the technique and quantifying the result.

Also, it should be recognized that the successful conduct of an experiment or operation is a difficult task that requires qualified scientists and operational personnel. It is difficult and expensive to fly aircraft safely in supercooled regions of clouds. It is also difficult to target the seeding agent from ground generators or from broad-scale seeding by aircraft upwind of an orographic cloud system.

Stratiform clouds

The seeding of cold stratiform clouds began the modern era of weather modification. Shallow stratiform clouds can be under certain conditions made to precipitate, often resulting in clearing skies in the region of seeding. Deep stratiform cloud systems (but still with cloud tops warmer than -20°C) associated with cyclones and fronts produce significant amounts of precipitation. A number of field experiments and numerical simulations have shown the presence of supercooled water in some regions of these clouds and there is some evidence that precipitation can be increased.

Cumuliform clouds

In many regions of the world, cumuliform clouds are the main precipitation producers. These clouds (from small fair weather cumulus to giant thunderclouds) are characterized by strong vertical velocities with high condensation rates. They can hold the largest condensed water contents of all cloud types and can yield the highest precipitation rates. Seeding experiments continue to suggest that precipitation from single-cell and multicell convective clouds have produced variable results. The response variability is not fully understood.

Precipitation enhancement techniques by glaciogenic seeding are utilized to affect ice phase processes while hygroscopic seeding techniques are used to affect warm rain processes. Methods to assess these techniques vary from direct measurements with surface precipitation gauges to indirect radar derived precipitation estimates. Both methods have inherent advantages and disadvantages.

During the last ten years there has been a thorough scrutiny of past experiments using glaciogenic seeding. The responses to seeding seem to vary depending on changes in natural cloud characteristics and in some experiments they appear to be inconsistent with the original seeding hypothesis.

Experiments involving heavy glaciogenic seeding of warm-based convective clouds (bases about +10°C or warmer) have produced mixed results. They were intended to stimulate updraughts through added latent heat release, which, in turn, was postulated to lead to an increase in precipitation. Some experiments have suggested a positive effect on individual convective cells but conclusive evidence that such seeding can increase rainfall from multi-cell convective storms has yet to be established. Many steps in the postulated physical chain of events have not been sufficiently documented with observations or simulated in numerical modelling experiments.

In recent years, the seeding of warm and cold convective clouds with hygroscopic chemicals to augment rainfall by enhancing warm rain processes (condensation/collision-coalescence/break-up mechanisms) has received renewed attention through model simulations and field experiments. Two methods of enhancing the warm rain process have been investigated: first, seeding with small particles (artificial CCN with mean sizes about 0.5 to 1.0 micrometers in diameter) is used to accelerate precipitation initiation by stimulating the condensation-coalescence process by favourably modifying the initial droplet spectrum at cloud base, and second, seeding with larger hygroscopic particles (artificial precipitation embryos about 30 micrometers in diameter) to accelerate precipitation development by stimulating the collision-coalescence processes. A recent experiment utilizing the latter technique indicated statistical evidence of radar estimated precipitation increases. However, the increases were not as contemplated in the conceptual model but seem to occur at later times (1-4 hours after seeding), the cause of this effect is not known.

Recent randomized seeding experiments with flares that produce small hygroscopic particles in the updraught regions of continental, mixed-phase convective clouds have provided statistical evidence of increases in radar-estimated rainfall. The experiments were conducted in different parts of the world and the important aspect of the results was the replication of the statistical results in a different geographical region. In addition, physical measurements were obtained suggesting that the seeding produced a broader droplet spectrum near cloud base that enhances the formation of large drops early in the lifetime of the cloud. These measurements were supported by numerical modelling studies.

Although the results are encouraging and intriguing, the reasons for the duration of the observed effects obtained with the hygroscopic particle seeding are not understood and some fundamental questions remain. Measurements of the key steps in the chain of physical events associated with hygroscopic particle seeding are needed to confirm the seeding conceptual models and the range of effectiveness of these techniques in increasing precipitation from warm and mixed-phase convective clouds.

Despite the statistical evidence of radar estimated precipitation changes in individual cloud systems in both glaciogenic and hygroscopic techniques, there is no evidence that such seeding can increase rainfall over significant areas economically. There are no evidence of any extra-area effects.

HAIL SUPPRESSION

Hail causes substantial economic loss to crops and property. Many hypotheses have been proposed to suppress hail, and operational seeding activities have been undertaken in many countries. Physical hypotheses include the concepts of beneficial competition (creating many additional hail embryos that effectively compete for the supercooled water), trajectory lowering (intended to reduce the size of hailstones), and premature rainout. Following these concepts, seeding methods concentrate on the peripheral regions of large storm systems, rather than on the main updraught.

Our understanding of storms is not yet sufficient to allow confident prediction of the effects of seeding on hail. The possibilities of increasing or decreasing hail and rain in some circumstances have been discussed in the scientific literature. Supercell storms have been recognized as a particular problem. Numerical cloud model simulations have provided insights into the complexity of the hail process, but the simulations are not yet accurate enough to provide final answers. Scientists in operational and research programs are working to delineate favourable times, locations, and seeding amounts for effective modification treatments.

A few randomized trials have been conducted for hail suppression using such measures as hail mass, kinetic energy, hailstone number, and area of hailfall. However, most attempts at evaluation have involved non-randomized operational programs. In the latter, historical trends in crop hail damage have often been used, sometimes with target and upwind control areas, but such methods can be unreliable. Large reductions have been claimed by many groups. The weight of scientific evidence to date is inconclusive, neither affirming nor denying the efficacy of hail suppression activities. This situation is motivation for operational programs to strengthen the physical and evaluation components of their efforts.

In recent years anti-hail activities using cannons to produce loud noises have re-emerged. There is neither a scientific basis nor a credible hypothesis to support such activities.

Significant advances in technology during the last decade have opened new avenues to document and better understand the evolution of severe thunderstorms and hail. New experiments on storm organization and the evolution of precipitation including hail are needed.

OTHER SEVERE WEATHER MODERATION

Tropical cyclones contribute significantly to the annual rainfall of many areas, but they are also responsible for considerable damage to property and for a large loss of life. Therefore, the aims of any modification procedure should be to reduce the wind, storm surge, and rain damage, but not necessarily the total rainfall. Hurricane modification experiments were conducted in the 1960s and early 1970s. However, there is no generally accepted conceptual model suggesting that hurricanes can be modified.

While modification of tornadoes or of damaging winds is desirable for safety and economical reasons, there is presently no accepted physical hypothesis to accomplish such a goal.

There has been some interest in the suppression of lightning. Motivation includes reducing occurrences of forest fires ignited by lightning and diminishing this hazard during the launching of space vehicles. The concept usually proposed involves reducing the electric fields within thunderstorms so that they do not become strong enough for lightning discharges to occur. To do this, chaff (metallized plastic fibres) or silver iodide have been introduced into thunderstorms. The chaff is postulated to provide points for corona discharge which reduces the electric field to values below those required for lightning, whereas augmenting the ice-crystal concentration is postulated to change the rate of charge build up and the charge distribution within the clouds. Field experiments have used these concepts and limited numerical modelling results have supported them. The results have no statistical significance.

INADVERTENT WEATHER MODIFICATION

There is ample evidence that biomass burning, agricultural and industrial activities modify local and sometimes regional weather conditions. Land-use changes (e.g. urbanization and deforestation) also modify local and regional weather. Air quality, visibility, surface and low-level wind, humidity and temperature, and cloud and precipitation processes are all affected by large urban areas. As environmental monitoring and atmospheric modelling capabilities are improved, it is increasingly evident that human activities have significant impacts on meteorological parameters and climatological mechanisms that influence our health, productivity and societal infrastructure. Inadvertent effects need to be considered in design and analyses of weather modification experiments and operations (e.g. changes in background aerosol distributions affect the cloud structure and may affect precipitation processes).

ECONOMIC, SOCIAL AND ENVIRONMENTAL ASPECTS OF WEATHER MODIFICATION

Weather modification is sometimes considered by countries when there is a need to improve the economy in a particular branch of activity (for example: increase in water supply for agriculture or power generation) or to reduce the risks that may be associated with dangerous events (frosts, fogs, hail, lightning, thunderstorms, etc.). Besides the present uncertainties associated with the capability to reach such goals, it is necessary to consider the impacts on other activities or population groups. Economical, social, ecological and legal aspects should be taken into account. Thus, it is important to consider all the important complexity and recognize the variety of possible impacts, during the design stage of an operation.

Legal aspects may be particularly important when weather modification activities are performed in proximity to borders of different countries. However, any legal system aimed at promoting or regulating weather modification must recognize that scientific knowledge is still incomplete.

The implications of any projected long-term weather modification operation on ecosystems need to be assessed. Such studies could reveal changes that need to be taken into account. During the operational period, monitoring of possible environmental effects should be undertaken as a check against anticipated impacts.

SUMMARY STATEMENT AND RECOMMENDATIONS

To answer the need for more water and less hail in many regions of the world, some progress has been made during the past ten years in the science and technology of weather modification. Large numbers of programmes in fog dispersion, rain, snow enhancement and hail suppression are in operation. Several research experimental programmes are supported in some countries and include randomized statistical evaluations. Improved observational facilities, computer capabilities, numerical models, and understanding now permit more detailed examination of clouds and precipitation processes than ever before, and significant advances are consequently possible. New technologies and methods are starting to be applied and will help to lead to further understanding and development in this field.

In the light of this review of the status of weather modification, the following recommendations are made to interested Members of WMO:

(a) Cloud, fog and precipitation climatologies should be established in all countries as vital information for weather modification and water resource studies and operations;

(b) Operational cloud-seeding projects should be strengthened by allowing an independent evaluation of the results of seeding. This should include measurements of physical response variables and a randomized statistical component;

(c) Education and training in cloud physics, cloud chemistry, and other associated sciences should be an essential component of weather modification projects. Where the necessary capacity does not exist advantage should be taken of facilities in other Members;

(d) It is essential that basic measurements to support and evaluate the seeding material and seeding hypothesis proposed for any weather modification experiments be conducted before and during the project;

(e) Weather modification programmes are encouraged to utilize new observational tools and numerical modelling capabilities in the design, guidance and evaluations of field projects. While some Members may not have access or resources to implement these technologies, collaboration between member states (e.g. multinational field programmes, independent expert evaluations, education, etc.) are encouraged that could provide the necessary resources for implementing these technologies.

ATTACHMENT 3

DRAFT WMO STATEMENT ON THE SCIENTIFIC BASIS FOR, AND LIMITATIONS OF, WEATHER AND CLIMATE FORECASTING

1. INTRODUCTION

1.1. Every day around the world, the National Meteorological Services (NMSs) and private sector meteorological service providers of the Member States and Territories of the World Meteorological Organization (WMO) provide hundreds of thousands of forecasts and warnings of weather and climate conditions and events. These forecasts and warnings provide information, for the benefit of the community at large and for a wide range of specialized user sectors, on a broad spectrum of atmospheric phenomena ranging from those with time scales of seconds to minutes and space scales of metres to kilometres, such as severe storms, through to those, such as El Niño related drought, with multi-year and global impact. The forecast information provided is used to inform and improve decision making in virtually every social and economic sector and the globally aggregated economic benefits of meteorological services are reckoned to be of the order of hundreds of billions of US dollars.

1.2. The capacity to provide these socially and economically beneficial services to the citizens of the 185 Members of the WMO results from the operation of the unique international system of cooperation of the WMO World Weather Watch which is based on:

- Collection and international exchange of the global observational data that are essential to describe the current (initial) state of the atmosphere (and the underlying land and ocean) at any point in time;
- The fact that the physical and dynamical processes governing the behaviour of the atmosphere and ocean can be represented in numerical models which are capable of providing forecasts of daily weather conditions with significant skill out to several days from the 'initial' state as well as useful indications, in certain circumstances, of general trends of climate for months and seasons ahead;
- The existence of a coordinated international meteorological system of global, regional and national data processing and modelling centres producing real-time products from which skilled professional forecasters are able to prepare forecasts and warnings in forms that are relevant and useful to the user community;
- The ability to monitor extreme events in real-time and to issue warnings by combining classical meteorological observations, model output and information from remote sensing systems such as satellites and radar.

1.3. The scientific understanding and technological capabilities underlying this globally cooperative system of weather and climate forecasting have made enormous progress over the past twenty-five years as a result, in particular, of such cooperative international research programmes as the WMO-ICSU (International Council for Science) Global Atmospheric Research Programme (GARP), the WMO World Weather Research Programme and the WMO-ICSU-IOC (Intergovernmental Oceanographic Commission of UNESCO) World Climate Research Programme (WCRP). The skill levels and utility of the resulting forecasts and warnings have steadily increased. Indeed three-day forecasts of surface atmospheric pressure are now as accurate as one-day forecasts twenty years ago. But the observational data base necessary to describe the 'initial' state of the atmosphere will always be limited by considerations of scale and measurement accuracy, the processes governing the behaviour of the atmosphere are non-linear and the phenomenon known as chaos imposes fundamental limits on predictability. While new techniques are emerging which help potential users of weather and climate forecasts to better understand, and make allowance for, the inherent uncertainties in the forecasts, the WMO Executive Council believes it is important that all those who make use of such forecasts in decision making should be made better aware of both their scientific foundation and their scientific and practical limitations. It therefore requested that the WMO Commission for Atmospheric Sciences (CAS) prepare a statement on the current status of weather and climate forecasting.

1.4. This statement has been prepared by CAS with input from other WMO and external scientific organizations and programmes including the WCRP. It was approved by the thirteenth session of CAS in Oslo in February 2002 and endorsed by the Executive Council at its fifty-fourth session in June 2002. It is provided for the information of all those with an interest in the scientific foundations and limitations of weather and climate forecasting on time scales from minutes and hours through to decades and centuries.

2. THE SCIENCE OF WEATHER FORECASTING

Dynamical and physical processes within the atmosphere, and interactions with the surroundings (e.g. land, ocean, and ice surfaces), determine the evolution of the atmosphere, and hence the weather. Scientifically based weather forecasts are possible if the processes are well enough understood, and the current state of the atmosphere well enough known, for predictions to be made of future states. Weather forecasts are prepared using a largely systematic approach, involving observation and data assimilation, process understanding, prediction and dissemination. Each of these components has, and will continue to benefit from advances in science and technology.

2.1 Observations and data assimilation

2.1.1 Over the past few decades, substantial advances in science have resulted in improved and more efficient methods for making and collecting timely observations, from a wide variety of sources including radar and satellites. Using these observations in scientifically based methods has caused the quality of weather forecasts to increase dramatically, so that people around the world have come to rely on weather forecasts as a valued input to many decision making processes.

2.1.2 Computer generated predictions are initialized from a description of the atmospheric state built up from past and current observations in a process called data assimilation, which uses the numerical weather prediction (NWP) model (see 2.3.2) to summarize and carry forward in time information from past observations. Data assimilation is very effective at using the incomplete coverage of observations from various sources to build a coherent estimate of the atmospheric state. But, like the forecast, it relies on the NWP model, and cannot easily use observations of scales and processes not represented by the model.

2.1.3 The international scientific community is emphasizing the still very poorly observed areas as being a limiting factor in the quality of some forecasts. As a consequence, there is a continued need for improved observation systems, and methods to assimilate these into NWP models.

2.2 Understanding of the atmosphere: inherent limitations to predictability

2.2.1 The scientific understanding of physical processes has made considerable progress through a variety of research activities, including field experiments, theoretical work, and numerical simulation. However, atmospheric processes are inherently non-linear, and not all physical processes can be understood or represented in NWP models. For instance, the wide variety of possible cloud water and ice particles must be highly simplified, as are small cumulus clouds that can lead to rain showers. Continued research effort using expected improvements in computer technology and physical measurements will enable these approximations to be improved. Even then, it will still not be possible to represent all atmospheric motions and processes

2.2.2 There is a wide spectrum of patterns of atmospheric motion, from the planetary scale down to local turbulence. Some are unstable and they are arranged so that flow is amplified using for example energy from heating and condensation of moisture. This property of the atmosphere means that small uncertainties about the state of the atmosphere will also grow, so that eventually the unstable patterns cannot be precisely forecast. How quickly this happens depends on the type and size of the motion. For convective motions such as thunderstorms the limit is of the order of hours, while for large scales of motion it is of the order of two weeks.

2.3 Weather Prediction

2.3.1 *Nowcasting*: Forecasts extending from 0 out to 6 to 12 hours are based upon a more observations-intensive approach and are referred to as nowcasts. Traditionally, nowcasting has focussed on the analysis and extrapolation of observed meteorological fields, with a special emphasis on mesoscale fields of clouds and precipitation derived from satellite and radar. Nowcast products are especially valuable in the case of small-scale hazardous weather phenomena associated with severe convection and intense cyclones. In the case of tropical cyclones, nowcasting is an important detection and subsequent short-term prediction approach that provides forecast value beyond 24 hours in some cases. However, the time rate of change of phenomena such as severe convection is such that the simple extrapolation of significant features leads to a product that deteriorates rapidly with time - even on time scales of order one hour. Thus methods are being developed that combine extrapolation techniques with NWP, both through a blending of the two products and through the improved assimilation of detailed mesoscale observations. These are inherently difficult tasks and, although accuracy and specificity will improve over coming years, these products will always involve uncertainty regarding the specific location, timing and severity of weather events such as thunder and hail storms, tornadoes and downbursts.

2.3.2 *Numerical Weather Prediction (NWP)*: Forecasts for lead times in excess of several hours are essentially based almost entirely on NWP. In fact, much of the improvement in the skill of weather forecasts over the past 20 years can be attributed to NWP computer models, which are constructed using the equations governing the dynamical and physical evolution of the atmosphere. NWP models represent the atmosphere on a three-dimensional grid, with typical operational systems in 2001 use a horizontal spacing of 50-100 km for large-scale forecasting and 5 to 40 km for limited area forecasting at the mesoscale. This will improve as more powerful computers become available.

Only weather systems with a size several times the grid spacing can be accurately predicted, so phenomena on smaller scales must be represented in an approximate way using statistical and other techniques. These limitations in NWP models particularly affect detailed forecasts of local weather elements such as cloud and fog, and extremes such as intense precipitation and peak gusts. They also contribute to the uncertainties that can grow chaotically, ultimately limiting predictability.

2.3.3 *Ensemble Prediction:* Uncertainty always exists - even in our knowledge of the current state of the atmosphere. It grows chaotically in time, with a gradual decay in the value of the new information introduced at the beginning, until only climatological information remains. The rate of growth of this uncertainty is difficult to estimate since it depends upon the three-dimensional structure of the atmospheric flow. The solution is to execute a group of forecasts - an ensemble - from a range of modestly different initial conditions and/or a collection of NWP models with different, but equally plausible, approximations. If the ensemble is well designed, its forecasts will span the range of likely outcomes, providing a range of patterns where uncertainties may grow. From this set of forecasts, information on probabilities can be derived automatically, tailored to users' needs.

Forecast ensembles are subject to the limitations of NWP discussed earlier. Additionally, since the group of forecasts are being computed simultaneously, less computer power is available for each forecast. This requires grid spacings to be increased, making it more difficult to represent some severe weather events of smaller horizontal scale. Together with the limited number of forecasts in an ensemble, this makes it harder to estimate probabilities of very extreme and rare events directly from the ensemble. Moreover it is not possible at present to modify the NWP models so they can sample modelling errors properly; so sometimes all models will make similar errors

2.3.4 *Operational Meteorologist:* There remains a critical role for the human forecaster in interpreting the output and in reconciling sometimes seemingly conflicting information from different sources. This role is especially important in situations of locally severe weather. Although vigorous efforts are being made to provide forecasters with good quality systems such as interactive workstations for displaying and manipulating the basic information, they still have to cope with vast amounts of information and make judgements within severe time constraints. Furthermore, forecasters are challenged to keep up to date with the latest scientific advances.

3. PREDICTION AT SEASONAL TO INTERANNUAL TIME-SCALES

3.1 Beyond two weeks, weekly average predictions of detailed weather have very low skill, but forecasts of one month averages, using NWP with predicted sea surface temperature anomalies, still have significant skill for some regions and seasons to a range of a few months.

3.2 At the seasonal time scale, detailed forecasts of weather events or sequences of weather patterns are not possible. As mentioned above, the chaotic nature of the atmosphere sets a fundamental limit of order two weeks for such deterministic predictions, associated with the rapid growth of initial condition errors arising from imperfect and incomplete observations. Nonetheless, in a limited sense, some predictability of temperature and precipitation anomalies has been shown to exist at longer lead times out to a few seasons. This comes about because of interactions between the atmosphere, the oceans, and the land surface, which become important at seasonal time scales.

3.3 The intrinsic time scales of variability for both the land surface and the oceans are long compared to that of the atmosphere, due in part to relatively large thermal inertia. Ocean waves and currents are slow in comparison to their atmospheric counterparts, due to the large differences in density structure. To the extent that the atmosphere is connected to the ocean and land surface conditions, then, a degree of predictability may be imparted to the atmosphere at seasonal time scales. Such coupling is known to exist particularly in the tropics, where patterns of atmospheric convection ultimately important to global scale weather patterns are quite closely tied to variations in ocean surface temperature. The most important example of this coupling is found in the El Niño/Southern Oscillation phenomenon, which produces large swings in global climate at intervals ranging from 2-7 years.

3.4 The nature of the predictability at seasonal time scales must be understood in probabilistic terms. It is not the exact sequence of weather that has predictability at long lead times (a season or more), but rather some aspects of the statistics of the weather – for example, the mean or variance of temperature/precipitation over a season – that has potential predictability. Though the weather on any given day is entirely uncertain at long lead times, the persistent influence of the slowly evolving surface conditions may change the odds for a particular type of weather occurring on that day. In rough analogy to the process of throwing dice, the subtle but systematic influence of the boundary forcing can be likened to throwing dice that are "loaded". On any given throw, we cannot foretell the outcome, yet after many throws the biased dice will favor a particular outcome over others. This is the sort of limited predictability that characterizes seasonal prediction.

3.5 Currently seasonal predictions are made using both statistical schemes and dynamical models. The statistical approach seeks to find recurring patterns in climate associated with a predictor field such as sea surface temperature. Such models have demonstrated skill in forecasting El Niño and some of its global climate impacts. The basic tools for dynamical prediction are coupled models – models that include both the atmosphere and the other media of importance, particularly the oceans. Such models are initialized using available observations and integrated forward in time to produce a seasonal prediction. The issue of uncertainty is handled using an ensemble approach, where the climate model is run many times with slightly different initial conditions (within the range of observation errors or sampling errors). From this a distribution of results is obtained, whereupon statistics of the climate can be estimated. Recently, encouraging results have been obtained from ensemble outputs of more than one model being combined.

3.6 There are several limitations associated with current predictions. Most coupled models (and to a lesser extent uncoupled models) exhibit some serious systematic errors that inevitably reduce forecast skill. Data availability is a limitation for both statistical models and for dynamical models. In the latter case, very limited information is available for much of the global oceans, and for the land surface conditions. Also, current initialization methods do not account properly for systematic model errors, further limiting forecast performance. A final set of limitations arises for practical reasons. Due to resource requirements, most seasonal predictions cannot be done at resolutions comparable to weather prediction. Further, rather small ensemble sizes (of order 10) are used for some models, certainly less than is optimal for generating robust probabilistic forecasts. Current research is addressing the potential for regional "downscaling" of climate forecasts by various means, and the possibilities for more detailed probabilistic climate information from expanded ensembles of one or more models.

3.7 Possible use of seasonal forecasts is currently being explored in various contexts. In each case, effective use will require careful attention to the issue of uncertainty inherent in seasonal forecasts. Future advancements can be expected to improve the estimates of uncertainty associated with forecasts, allowing better use of forecast products.

4. PROJECTION OF FUTURE CLIMATE

4.1 As explained above, based on the current observed state of the atmosphere, weather prediction can provide detailed location and time specific weather information on timescales of the order of two weeks. Some predictability of temperature and precipitation anomalies has been shown to exist at longer lead times out to a few seasons. This comes about because of interactions between the atmosphere, the oceans, and the land surface, which become important at seasonal time scales. At longer timescales the current observed state of the atmosphere and even those large scale anomalies which provide predictive skill at seasonal to interannual timescales are no longer able to do so due to the fundamental chaotic nature of the earth-atmosphere system. However, long term changes in the earth-atmosphere system at climate timescales (decades to centuries) are dependent on factors which change the balance of incoming and outgoing energy in the earth-atmosphere system. These factors can be natural (e.g., changes in solar output or volcanoes) or human induced (e.g., increased greenhouse gases). Because simulations of possible future climate states are dependent on prescribed scenarios of these factors they are more accurately referred to as "projections" not "predictions" or "forecasts".

4.2 In order to perform climate projections, physically-based climate models are required in order to represent the delicate feedbacks which are crucial on climate timescales. Physical processes and feedbacks that are not important at NWP or even at the timescales of seasonal prediction become crucial when attempting to simulate climate over long periods, e.g., cloud-radiation interaction and feedback, water vapour feedback (and correctly modelling long-term trends in water vapour), ocean dynamics and processes (in particular an accurate representation of the thermohaline circulation). The treatments of these key features are adequate to reproduce many aspects of climate realistically though there remain many uncertainties associated with clouds and aerosols and their radiative effects, and many ocean processes. Nevertheless, there is reasonable confidence that state-of-the-art climate models do provide useful projections of future climate change. This confidence is based on the demonstrated performance of models on a range of space time scales.

4.3 Notably, the understanding of key climate processes and their representation in models (such as the inclusion of sea-ice dynamics and more realistic ocean heat transport) has improved in the past few years. Many models now give satisfactory simulations of climate without the need for non-physical adjustments of heat and water fluxes at the ocean-atmosphere interface used in earlier models. Moreover, simulations that include estimates of natural and anthropogenic forcing are well able to reproduce observed large-scale changes in surface temperature over the twentieth century. This large-scale consistency between models and observations lends confidence in the estimates of warming rates projected over the next century. The simulations of observed natural variability (e.g., ENSO, monsoon circulations, the North Atlantic Oscillation) have also improved.

4.4 On the other hand, systematic errors are still all too apparent, e.g., in simulated temperature distributions in different regions of the world or in different parts of the atmosphere, in precipitation fields, clouds (in particular marine stratus). One of the factors that limits confidence in climate projections is the uncertainties in external forcing (e.g., in predicting future atmospheric concentrations of carbon dioxide and other greenhouse gases, and aerosol loadings).

4.5 As with NWP and seasonal forecasts, ensembles of climate projections are also extremely important. Ensembles enable the magnitude and effects of natural climate variability to be gauged and its impact on future projections, and thereby permit any significant climate change signal to be picked out more clearly statistically (the magnitude of natural climate variability will be comparable with that of climate change for the next few decades).

5. DISSEMINATION TO END-USERS

5.1 The weather forecasts have to be communicated to a vast array of users such as emergency managers, air traffic controllers, flood forecasters, public event managers, etc., in a timely and user-applicable form. This in itself poses another major challenge that is increasingly benefiting from advances in information technology. Predictions at seasonal to interannual timescales and climate projections are also being used by an increasingly wide range of users.

5.2 The value of forecasts to decision-makers is greatly enhanced if the inherent uncertainty can be quantified. This is particularly true of severe weather, which can cause such damage to property and loss of life that precautions may be well advised even if the event is unlikely, but possible. Probabilities are a natural way of expressing uncertainty. A range of possible outcomes can be described with associated probabilities, and users can then make informed decisions allowing for their particular costs and risks.

5.3 Forecasts expressed as probabilities, or ensembles, contain much more information than deterministic forecasts, and it is difficult to convey it all to users. Broadcast forecasts can only give a broad picture of the most likely outcome, with perhaps some idea of important risks. Each user's decision may be based on the probabilities of a few specific occurrences. What these are, and the probability thresholds for acting on the forecasts, will differ. So for important user decisions it is necessary to apply their particular criteria to the detailed forecast information.

6. CONCLUSIONS

6.1 The skill in weather forecasting has advanced substantially since the middle of the 20th century, largely supported by the advancement of computing, observation (radar and satellite, in particular), and telecommunications systems, and the development of numerical weather prediction models along with the associated data-assimilation techniques. This has been greatly facilitated because of the vast experience of both forecasters and decision-makers in producing and using forecast products. Nevertheless, each component within the science and technology of weather forecasting and climate projection has its own uncertainties. Some of these are associated with a lack of a complete understanding of, or an inherent limitation of the predictability of highly complex processes. Others are linked still to the need for further advances in observing or computing technology, or an inadequate transfer between research and operations. Finally, one cannot under-estimate the importance of properly communicated weather forecasts to well-educated users.

6.2 Without a doubt, significant benefits will result from continued attention to scientific research and the transfer of knowledge gained from this work into the practice of forecasting. Furthermore, a recognition of the limitations of weather forecasts and climate projections, and when possible an estimate of the degree of uncertainty, will result in the improved use of forecasts and other weather information by decision-makers. Ultimately the objective is for the scientific and user communities to work better together, realizing even greater benefits.