Australian Meteorological and Oceanographic Society (AMOS)
Statement on Weather Analysis and Prediction in Australia

This statement provides a summary of some aspects of weather analysis and prediction, with particular focus on Australia. It has been compiled by atmospheric and oceanographic scientists, reviewed by Members of the Australian Meteorological and Oceanographic Society (AMOS), and approved by the AMOS Council as an official AMOS position statement. The statement will expire 5 years from its adoption, or earlier as determined by AMOS Council.

Weather forecasts arm people with the advanced warning needed to protect life and property, make important commercial decisions, or to simply make everyday choices such as what to wear each morning. Forecasts are essential for disaster resilience, emergency services, improved public health, defence, energy management, aviation, and of course agriculture, among many other sectors and activities. Weather forecasts are an indispensable part of modern life.

In Australia, the Bureau of Meteorology (BoM) has statutory responsibility for making and issuing weather forecasts and warnings. A recent study by London Economics estimated that, "for every dollar spent on delivering Bureau [of Meteorology] services, these services return a benefit of $11.60 to the Australian economy."

Some private sector companies complement these taxpayer-funded services by customising forecasts for industry and other users. Research into the underpinning science of weather and its application to weather prediction is conducted in Australian universities, the Commonwealth Scientific and Industrial Research Organization (CSIRO), and of course the BoM. In addition, the universities and the BoM train the nation's future generation of meteorologists.

1. How is the Weather Predicted?

Weather means the state of the atmosphere, from large-scale features that move around the planet (for example, low pressure systems and cold fronts) to smaller scale features (for instance, sea breeze circulations and thunderstorms), to very fine scale turbulence (such as the clear air turbulence that occasionally affects aircraft). Like all of nature, the weather is governed by the laws of physics. To make the problem solvable on a computer, *numerical weather prediction* approximates and solves these laws at discrete points in space and time on a spatial grid covering the Earth. Nonetheless, physical processes on scales close to or smaller than the grid spacing are too small to be resolved explicitly and must be incorporated through physically/empirically based formulations or *parameterize*d. These unresolved physical processes include solar and infrared radiation, the effect of the Earth's surface (land and ocean) on the overlying atmosphere, and the physical processes associated with clouds, storms and rain. Much of the predictive skill of the computer models hinges on how well the unresolved physical processes are represented by the parameterizations.

Numerical weather prediction is not the only way forecasts are made. Forecasts for a few minutes to a few hours, called *nowcasts*, are usually based on statistical extrapolation of observations from radar, satellite, lightning networks and conventional instruments. Nowcasts are made most often for rain and thunderstorms. Increasingly, observation-based nowcasts are blended with short-range computer model forecasts to generate short-term forecasts.

Forecasters play a key role in integrating, interpreting and communicating the information from model predictions and nowcasts as weather forecasts and warnings to the general public and specific users, particularly in times of severe weather, such as tropical cyclones. Forecasters also use their local knowledge to adjust the objective forecasts (for example, fog prediction for the aviation industry) or to make specialized forecasts for a particular place (such as fire weather forecasts for firefighters). In addition to the output from the suite of models operating on the Bureau's supercomputer, forecasters in Australia have access to the predictions from at least four international computer models that are shared by national weather agencies around the world in real-time.

2. The Importance of Observations and the Initial State

Making a weather forecast requires a detailed knowledge of the current state of the atmosphere (e.g., wind, temperature, pressure, water content), land surface and ocean; this current state is known as the *analysis*. The main sources of input data for numerical weather forecasts are radiosondes (weather balloons) and satellites, as well as commercial aircraft, floating buoys, ships, radars and manual and automated weather stations.

The analysis blends observations with short-term computer model forecasts for the current time, taking into account estimates of their respective errors, a process known as *data assimilation*. Weather forecasts can be highly sensitive to small changes in the analysis. The observations used to construct the analysis are affected by instrumental and sampling errors, and these initial errors often result in forecast errors which can amplify in time.

One way to make more useful forecasts in the face of this sensitivity is to make a number of separate forecasts, each starting from a slightly different estimate of the current state, which taken together, encompass the range of possible initial conditions. The resulting forecasts should encompass the range of possible outcomes, thereby providing an error bar on the forecast. This process is known as *ensemble forecasting*, and the forecasts can be used to estimate the probability of a particular outcome (for example, rain exceeding a certain amount). Additional uncertainty in the forecasts can be taken into account by introducing small fluctuations (stochastic physics) into the physical parametrizations.

3. Improvements in Weather Forecasts

The success of a scientific theory is, in part, judged by its capacity to make accurate predictions. Every day our scientific understanding of physical processes in the atmosphere is tested by making weather forecasts. The process of assessing the success or otherwise of these forecasts is known as *verification*.

The great advances in weather prediction over the past few decades have been due principally to improvements in the analyses (especially improved satellite sensing of the atmosphere, land and ocean, and data assimilation), physical parameterizations, and ensemble prediction. Moreover, improving the horizontal and vertical resolution of the grid representing the atmosphere and the underlying topography produces a more detailed and accurate representation of weather features. Five-day predictions are typically as accurate as 3-day predictions were twenty years ago, with the most rapid improvement occurring for the Southern Hemisphere. Nonetheless, weather forecasts in the tropics are still significantly less accurate than those in the mid and higher latitudes.

Along with the dramatic advances in numerical weather prediction, there has been a corresponding improvement in public weather forecasts. In the mean, current 5-day forecasts for Melbourne's maximum and minimum temperature have similar skill as 1-day forecasts from 40 years ago. Large maximum temperature errors of 5^{o}C or more have decreased from approximately 10% of the total number of forecasts forty years ago, to less than 1% in recent years. Rainfall forecasts are still difficult and, although they too have improved, more work is required.

Nowcasting has also benefited from advances in observational technology. Australia now has automatic weather stations reporting as frequently as every minute, 10-minute geostationary satellite imagery, a network of weather radars measuring rainfall and in some cases wind profilers that monitor upper-level winds and temperature, and wind measurements from aircraft.

4. Technological Requirements

The computer model used by the BoM to forecast the weather has approximately 1 million lines of code. A typical 10-day forecast requires the computer to solve the governing laws of physics every 10 minutes (1,440 time steps) at more than 50 million points on the globe (approximately 25 km spacing). Moreover, within a given 6-hour time window, 3-4 million observations of varying quality are assimilated.

The peak speed of the supercomputer currently used by the BoM is 1.66×10^{15} floating point operations per second[1]. The computer model used by the BoM typically uses 2160 computer nodes with 128 Gb of memory per node. In rough terms, this configuration is one million times faster and has half a million times more memory than a fast home PC (in 2016).

5. Directions and Challenges

- *International Collaboration.* Modern weather analysis and prediction is a truly international venture, made possible only by sharing meteorological data and scientific knowledge. For example, the observations taken by Australia are shared internationally and in turn extensive and expensive observations (funded principally by the US, Europe and Japan) are shared with Australia. As another example, the Australian Community Climate and Earth-System Simulator (ACCESS, used by the BoM to make numerical weather forecasts) is based on the weather forecasting model developed by the UK Met Office. Australia must continue to collaborate internationally otherwise the nation's capacity to forecast the weather would be very much poorer.

- *Parameterization.* The skill of numerical weather prediction depends critically on the parameterizations used. Although with higher model resolution some processes such as localised heavy rain and thunderstorms will become better represented, improving parameterizations remains a critical research area in numerical weather prediction. Arguably the parameterization most in need of improvement is the representation of convective processes leading to thunderstorms and showers.

- *Ensemble prediction.* There are theoretical reasons to believe that two weeks is about the limit of a single prediction regardless of the grid resolution. Ensemble forecasts can provide useful probabilistic information beyond this range. How best to construct and use ensemble forecasts remains an active research area, including how to meaningfully communicate probabilistic forecasts to the public.

- *High impact weather.* High-resolution, short-term forecasts, particularly for severe weather and its impacts, will continue to be a major area of development in Australia and elsewhere.

- *Urban weather*. Most Australians live in urban environments. Adapting current numerical weather models to take greater account of the effects of the built environment on the local weather will be an area of research, opening the possibility of improved air quality and localized flooding predictions. Weather forecasts in the urban-rural interface will focus on the likelihood of bushfires and bushfire behavior.

---

[1] A floating point operation is a mathematical operation such as addition or multiplication on a decimal number.

- *Convergence of weather, seasonal and climate forecasting.* The atmospheric models used for weather prediction, seasonal prediction and climate projections are fundamentally the same. They all solve the governing laws of physics at discrete points in space and time, and parameterize unresolved physical processes. These three types of numerical model are converging towards a single unified modelling approach known as *seamless prediction*. A capacity for seamless prediction in Australia is being built around ACCESS, which is a collaborative venture between the Australian Bureau of Meteorology, the CSIRO and the university sector. Achieving seamless prediction will continue to be an important area of activity and research.

- *Computational demands.* As the volume of observations and the complexity and resolution of computer models increase, so will the necessary speed, memory and bandwidth of the computational resources. The power demand may place a practical constraint on future numerical weather prediction models. For example, the supercomputer presently used by the UK Met Office to make its numerical weather forecasts consumes electricity at about the same rate as 1000 average Australian households.

- *Tailored information and effective communication.* How can meteorological information be tailored to the user community? There will be greater emphasis on adding value to raw computer model forecasts. Likewise, social media and mobile platforms could be used for targeting forecasts and warnings to the public and specific user groups.

- *Citizen observations.* There are opportunities for public and private sector forecasters to use citizen observations such as those from mobile communication devices that can take and send measurements of pressure, allowing people to report unusual or extreme weather. Although the quality of citizen observations requires careful monitoring, the density of citizen observers is potentially far greater than any established weather station networks.

- *Verification.* Comprehensively verifying all forecasts made by both the public and private sectors is important. Testing the capacity of the computer models to make accurate predictions and publishing the results have been important drivers of the technological advances in the science.

- *Advances in remote sensing.* Remote sensing applications (both space and surface based) continue to develop at great pace. Specific examples are the new generation of geostationary satellites with ten-minute imagery and many additional channels and plans by the BoM to add dual polarization capability to its radar network. There is a challenge to capture and process the larger data volumes and translate the extra data into weather analysis and prediction, particularly into nowcasting and warning services that protect and benefit the community.