Improving Seasonal Forecasts for SWWA

Final Report on the Managing Climate Variability project for GRDC

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Contents

Abstract ................................................................................................................................................ 3
Introduction .......................................................................................................................................... 4
Response to Objectives .......................................................................................................................... 5
1. Improve prediction of early, mid and late growing season rainfall in distinct climate regions insouth-west Western Australia relevant to the wheat industry using a global circulation model. ...... 5
2. Establish estimates of forecast uncertainty based on the range of model forecasts, the range ofon-farm outcomes, and benchmarking against existing forecast schemes..................................... 6
3. Improve predictability of soil moisture, yield and pasture growth through linking seasonalforecasts to farm practice, soil type and existing information such as stored soil moisture. .......... 7
4. Improve articulation of cereal farm practice options, with potential spin-offs to the grazingindustry, based on forecast skill and reliability. .................................................................................. 8
5. Establish foundations for ongoing strategic investment in improvement of global circulationmodels ............................................................................................................................................. 9
Output .................................................................................................................................................. 10
Publications ......................................................................................................................................... 10
Presentations ........................................................................................................................................ 10
Media .................................................................................................................................................. 12
Acknowledgements .............................................................................................................................. 12
References .......................................................................................................................................... 12
List of Attachments .............................................................................................................................. 12
List of Appendices .............................................................................................................................. 13
Appendix A. Interactions with farming community ..................................................................................... 14
   What do farmers want from forecasts? ............................................................................................. 14
   References ......................................................................................................................................... 16
Appendix B. POAMA development ........................................................................................................ 16
   Benchmarking POAMA-1.5 ............................................................................................................. 16
   POAMA-2 development .................................................................................................................. 17
   Performance ..................................................................................................................................... 18
   Issues ............................................................................................................................................... 20
Appendix C. Climate and model diagnostics .......................................................................................... 21
   Synoptic Analysis and Climatology ................................................................................................. 21
   Blocking .......................................................................................................................................... 24
   POAMA-1.5 rainfall forecast skill ...................................................................................................... 27
   POAMA-2 rainfall skill ..................................................................................................................... 38
   Ensemble Spread .............................................................................................................................. 40
   References ........................................................................................................................................ 41
Appendix D. Value of POAMA for N management in wheat ................................................................. 42
Appendix E. Break-even time and forecast pay-off time ......................................................................... 44
Appendix F. Value of POAMA for mixed farming ............................................................................... 49
Appendix G. Value of short-term rainfall forecasts .............................................................................. 49
Appendix H. Frost damage .................................................................................................................... 52
   Frost damage and crop simulation modelling .................................................................................. 52
   Crop simulation model ..................................................................................................................... 52
   Results ............................................................................................................................................. 53
   Climatology and frost occurrence .................................................................................................. 55
   References ........................................................................................................................................ 56
Appendix I. Value of POAMA for determining cultivar ......................................................................... 56
Appendix J. Future directions ................................................................................................................ 57
Appendix K. Project Proposal: Summary, Objectives, Outputs ............................................................. 59
   Project summary .............................................................................................................................. 59
   Project objectives ............................................................................................................................ 59
   Outputs .......................................................................................................................................... 59
   Outcomes ....................................................................................................................................... 59
Abstract

Forecasts of important climate variables such as rainfall can be of considerable value to the grains industry in the wheat belt of Western Australia. Management decisions such as sowing time, cultivar selection, fertiliser application and disease treatment can be made more efficiently when a monthly or seasonal forecast is available. Studies using idealised forecasts show that some management decisions have more to gain from a forecast than others. Australia’s seasonal climate forecast model, POAMA, is used to demonstrate the value of a real, imperfect forecast system. The model is shown to have skill at forecasting seasonal rainfall in the southern part of the WA wheat belt that equals or exceeds a suite of benchmark models. However, skill in the northern part of the wheat belt is only marginal. Climatological analysis of observations and the model (Pook et al. 2010, 2011) indicates that this is likely to be due to model difficulty in representing one of the key rain-bearing weather systems, the cutoff low, and this is associated with a common model difficulty in simulating atmospheric blocking.

Previous studies of the value of basing nitrogen fertiliser (N) application rates on a climate forecast have assumed a maximum rate of N application. This study uses a more realistic and conservative strategy where the expected return from adding $1 of N is typically $2. Using a POAMA-1.5 model forecast in this case achieves a long-term return of more than $50/ha in the southern wheat belt (Asseng et al. 2011a). Similar returns are demonstrated for mixed wheat/sheep farming (Asseng et al. 2011b). The payoff time for using such a forecast is shown to be 7 years at 95% confidence, or 3 years at 80% confidence (McIntosh et al. 2010a, b; McIntosh et al. 2011).

Multiple model runs are used to generate an ensemble of forecasts and hence an estimate of forecast skill. It is shown that for POAMA-1.5, the ensemble generation method is inadequate and leads to over-confident forecasts.

A new version of POAMA is developed that removes some of the sea-surface temperature bias inherent in such a coupled model. Model bias can lead to lower forecast skill and unrealistic forecast spread. Further improvements have been made to the data assimilation (initialisation) method, and to the ensemble generation method (Lim et al. 2010; Yin et al. 2011). When combined with two other model configurations to form a multi-model ensemble, POAMA-2.4, the ensemble spread is improved considerably despite the rainfall forecast skill remaining about the same.

The value of short-term (multi-week as opposed to seasonal) forecasts varies depending on the management decision. Dry sowing based on an idealised short-term forecast can lead to a benefit of $10-100 /ha. When applied to determining late-season N or fungicide to control disease, a short-term forecast can have a wide range of benefits from $10-160 /ha (Asseng et al. 2011c). However, a short term forecast is likely only to be of benefit for managing frost risk in severe frost risk areas because of the substantial penalty for late sowing (Farre et al. 2010).

Future directions for promising research in this area have become clear during the project. POAMA forecast skill is likely to be increased by: improving further the ensemble generation method; reducing the climatological model bias; improving the simulation of rain-bearing weather systems; more accurate model initialisation; and increasing the length of hindcast model runs. The transition of the dynamical components of POAMA to the ACCESS model will be a key step towards realising some of these goals. More realistic ensemble forecast spread should lead to greater value from uncertain forecasts. An improved initialisation method and reduced bias should allow an increase in skill at short lead times, with the challenge then to understand how best to make practical use of these forecasts for the wheat industry. There are promising signs that improved simulation of weather systems should give greater skill in the northern wheat belt. Finally, there is the prospect that longer hindcasts will allow the assessment of more complicated management decisions involving multiple factors.
Introduction

Farm income from dryland cropping can vary substantially from year to year due to climate variability. There are a number of farm management options that can be adjusted to cope with different season types if some information about the season is known in advance. Seasonal climate forecast models are now available that are beginning to have enough skill to be of value to farmers. This project explores ways of using existing seasonal climate forecasts from the Predictive Ocean Atmosphere Model for Australia (POAMA) model to increase farm income from cropping enterprises in south-west Western Australia. The project also aims to contribute substantially to the long term improvement of model forecasts by analysing model strengths and weaknesses to inform model development.

Farm management decisions available to grain farmers to address climate variability include sowing time, cultivar choice, fertiliser application (both at sowing time and later in the season), disease control and mixed wheat/grazing. Better decisions could be based on short-term and seasonal forecasts of rainfall and temperature. Forecasts are not, and never will be, perfectly accurate. This project aims to determine which management decisions could benefit from a forecast, and which forecasts are sufficiently skilful to be of value.

Seasonal forecast models were originally based on the statistics of the observed climate, but are now undergoing a transition to dynamical models that simulate climate physics. It is argued that statistical models are close to reaching the limit of their skill, and that this skill might even decrease because of the effect of climate change. Statistical models rely on the past as a guide to the future, and climate change undermines this assumption. Dynamical models are complicated systems of computer programs based on individual sub-systems that model the ocean, atmosphere, land surface and sea-ice. Additional components are needed to assimilate observations to start the models, and to generate a range of similar starting points that simulate dynamical uncertainty in a realistic fashion.

The process of developing, analysing and improving forecast models is lengthy and difficult because of their complexity. It is exacerbated by the substantial computer time taken to assess any changes. The interaction between model components is not straightforward, and making a local improvement to one component may result in an overall decline in skill. However, the lesson from numerical weather prediction is that by careful attention to the accurate representation of physical and dynamical processes in all components of the model, forecast skill will increase over time. This process can take a number of years to make a noticeable difference, but model improvement does happen and is substantial in the long term.

One of the key advances in this project is the development of a new ensemble generation method. Ensembles are generated to represent the chaotic growth of uncertainty in forecasts. By capturing this source of spread in forecasts we can better represent the true uncertainty, and in turn exploit this information for better farm management decisions. The existing ensemble method is known to under-represent the forecast spread over time so that POAMA is over-confident about the forecast, failing to represent the full range of possible outcomes. Methods for generating ensemble forecasts are at the forefront of research in seasonal forecasting. A new method is developed that incorporates work done as part of this project. It involves combining different versions of the POAMA model, one of which is funded by this project. The result is a new set of ensemble hindcasts (retrospective forecasts) that have a much more realistic model spread. This development came too late to be tested with application to the wheat industry, but it is likely to provide better forecast error estimates in the future.

This report is structured to specifically address the project objectives in a succinct and efficient manner, with much of the detail contained in appendices. A great deal of the scientific achievement in this project has also been written up in scientific manuscripts and conference papers. There are 6 manuscripts (two published, one submitted and three in the final stages of preparation) and 6 conference papers attached to this report in pdf form.
Response to Objectives

1. Improve prediction of early, mid and late growing season rainfall in distinct climate regions in south-west Western Australia relevant to the wheat industry using a global circulation model.

Meetings with farmers in the southern and northern regions of the WA wheat belt confirmed the importance of rainfall forecasts for the wheat industry (see Appendix A). Farmers in the northern region had a preference for short-term (several weeks to several months) forecasts for tactical decisions such as dry-sowing, early and late season N application, cultivar choice and fungicide application. Farmers in the southern region were more interested in a seasonal (May-Oct) forecast of rainfall and frost risk, but would also benefit from shorter-term forecasts for dry sowing and tactical N application. This project uses forecasts provided by Australia’s POAMA model.

POAMA is a dynamical seasonal climate forecast system run operationally by the Bureau of Meteorology. It consists of a global coupled ocean/atmosphere/land-surface/sea-ice model, a data assimilation sub-system and an ensemble generation sub-system. The existing version, POAMA-1.5, consists of a set of retrospective forecasts (hindcasts) that span the years 1980-2006. This hindcast set contains a comprehensive range of model output for forecasts starting every month and extending for 9 months. These data are suitable for testing model skill and agricultural value over the 27 year period.

The skill of POAMA-1.5 has been tested against a range of other forecast models and a few statistical forecast systems (see Appendix B), and against observations (see Appendix C). In particular, the skill at predicting the agriculturally-important seasonal rainfall in May-Oct from a 1 May start is examined. In the southern wheat belt in WA, POAMA-1.5 has greater or equal skill than all other forecasts at predicting above or below median seasonal rainfall. The number of correct forecasts is 70-78%. POAMA’s skill at predicting three or more categories is diminished because of the limited number of years available. Newer versions of POAMA developed during this project will eventually have about 20 additional years of output, although it is more difficult to produce reasonable hindcasts in earlier years because of the limited data for model initialisation.

In the northern wheat belt, POAMA-1.5 is found to have little useful skill. Although a couple of other forecast systems have some skill in the north, they are less skillful than POAMA-1.5 in the southern region. The reason for POAMA’s low skill in the northern region can be explained by its difficulty in simulating one of the important rain-bearing synoptic systems, the cutoff low, in this region. The rainfall in the southern region is dominated by cold fronts, whereas both cold fronts and cutoff lows are important in the northern region (see Appendix C and Pook et al. 2011). The simulation of cutoff lows is related to the ability of the model to simulate atmospheric blocking and the split jet in the atmosphere. All climate models have trouble simulating these features, and POAMA is no exception. There is a need to simulate the mean climate better in these models in order to improve the simulation of important synoptic systems (Scaife et al. 2010).

During this project, a new version of the model, POAMA-2.4, has been developed (see Appendix B, Lim et al. 2010 and Yin et al. 2011) with many improvements to the overall climate simulation, but there has been no improvement over POAMA-1.5 in rainfall forecast skill for May-Oct in southwest WA (SWWA) (see Appendix C). However, skill later in the year has improved considerably, as has the skill of longer lead time forecasts. The improvement can be attributed to better simulation of tropical drivers and processes. The problems with short lead time skill are thought to be related to the way in which the atmospheric conditions are perturbed over different ensemble members. This issue is now being explored.

One big improvement with POAMA-2.4 is the reliability, a measure of the ensemble spread. This is discussed in the next objective.
2. Establish estimates of forecast uncertainty based on the range of model forecasts, the range of on-farm outcomes, and benchmarking against existing forecast schemes.

As indicated in the previous objective, POAMA-1.5 has been benchmarked against other forecast systems in the wheat belt of WA (see Appendix B). It does very well in the southern wheat belt, but has little useful skill in the northern region. In the south, it can correctly predict above or below median rainfall in 19 out of 27 years. This level of skill is of considerable benefit to agriculture in the region.

Each hindcast is run 10 times with slightly different initial conditions to represent the uncertainty in the measured starting conditions. Generally the ensemble mean is used as the forecast, and it was hoped that the spread of the ensemble members might be indicative of the accuracy of individual forecasts. This has not been the case (see Appendix C), and the cause is likely to be the rather simple way in which the different starting conditions are specified. The new model, POAMA-2.4, has a much more complex method for generating the ensemble members (Lim et al. 2010; Yin et al. 2011), and this has improved the statistical reliability of the ensemble spread (see Appendix B, Figure B4). Since this is a very recent development, there has not been time to explore the benefit to agricultural prediction and value, but the indications are promising.

There are a number of very important questions related to the variability of on-farm outcomes that have been dealt with in this project. The first relates to the up-front nitrogen (N) application strategy. Consultations with farmers discovered that they adopt a very conservative approach whereby they will only add $1 of N if they expect to receive $2 benefit in return based on long-term climatology. They could add more N but it increases the risk. Using the APSIM wheat model and typical farm parameters and prices, the break-even time has been calculated (see Appendix E). With the conservative strategy, a farmer can be 95% sure of breaking even after 3 years, whereas adopting a riskier N strategy increases the break-even time to 6 years. This helps explain why farmers are risk averse – they minimise the risk of a run of loss years that might lose the farm.

Using the POAMA-1.5 seasonal rainfall forecast to determine the N application rate increases the break-even time by just one year, but increases the long-term farm income by 71%. Looked at another way, a typical farmer makes 80% of his/her income in 40% of the years without a forecast, but can make the same income using POAMA in just 15% of years. Hence the forecast is providing a real hedge against climate change if the number of good years declines (see Appendix E).

Finally, the break-even time for using a POAMA forecast was calculated. At the 95% confidence level, a farmer would have to follow a forecast for 7 years to be confident of obtaining a benefit. At the 80% confidence level, this time is only 3 years (see Appendix E).
3. **Improve predictability of soil moisture, yield and pasture growth through linking seasonal forecasts to farm practice, soil type and existing information such as stored soil moisture.**

Ultimately, improved predictability of soil moisture, yield and pasture growth flow through to improved gross margins in a wheat or wheat/sheep based farming system. The APSIM model (Keating et al. 2003) has been used to simulate wheat crops grown in the four main soil types in WA, and a range of up-front N application rates used to span the range of observed farm practice. The benefits of using a short-term 10 day idealised forecast to inform dry-sowing were then determined for dry and wet initial soil water conditions at the start of the season (see Appendix G and Asseng et al. 2011c).

Dry-sowing based on a forecast can have a benefit of $10-100/ha. Averaged over all four soil types, if the initial soil water conditions are wet the forecast gives an advantage of $15/ha at Katanning and $45/ha at Nyabing in the southern wheat belt. If the initial soil water conditions are wet, the forecast value drops to near zero, with Katanning losing $10/ha and Nyabing gaining $10/ha.

However, if a forecast is only used when the prediction is for a wet season, the benefit of a forecast improves considerably. For initially wet soils, the value is now around $50/ha at both sites, and for dry soils it is around $40/ha. The reason for this is that the gains in wet seasons are generally higher than the savings from reduced fertiliser in dry seasons.

Early work on establishing the value of short-term forecasts to late-season N application and fungicide application indicate a potential value of A$10-A$160/ha (see Appendix G and Asseng et al. 2011c).

The advantage of a forecast to crop yield is captured through the increased gross margins reported in another manuscript prepared as part of this project (Asseng et al. 2011a, see also Appendix D). Typical values are around $50/ha by using POAMA seasonal forecasts to determine an N strategy for above or below median rainfall years.

Similar advantages are obtained in a mixed wheat-sheep farming enterprise, where the forecast is used to trade-off the proportion of land area used for pasture for sheep or used for wheat. Another manuscript prepared as part of this project gives details (Asseng et al. 2011b, see also Appendix F). Values obtained could be as high as $66/ha.
4. Improve articulation of cereal farm practice options, with potential spin-offs to the grazing industry, based on forecast skill and reliability.

In consultation with farmers in the WA wheat belt, it was determined that a typical N management strategy was quite conservative, certainly more conservative than is typically used in assessing the value of a forecast system. Previous projects and forecast assessments have almost exclusively used a maximum N amount to obtain the highest possible gross margins, and then used a forecast to assess the incremental value (e.g. McIntosh et al. 2007; Moeller et al. 2008). Often the incremental value is quite low.

In this project a more realistic N management strategy is used, where a farmer will only apply $1 N if the return is substantially greater (typically $2). It is found that this realistic strategy makes a seasonal rainfall forecast much more valuable (See Appendix D and Asseng et al. 2011a). For example, at Nyabing, a POAMA forecast will only make an additional $10,000 on a typical 2500ha farm if the maximum amount of N is applied. However, if the farmer adopts a more realistic N application strategy of $1 N for $2 return, the same forecast is worth $167,000. Similar encouraging results are to be found in mixed wheat/sheep enterprises, with forecast values as high as $66/ha (see Appendix F and Asseng et al. 2011b). This is obtained by balancing pasture and wheat crop areas depending on the forecast season while maintaining the number of sheep. This effectively alters the stocking rate without the cost of buying and selling animals.

The finding that a moderately skilful seasonal rainfall forecast can be quite valuable in practice is one of the most exciting and important results of this project. It changes the way in which forecast value should be assessed in the real world, and demonstrates that POAMA has real value despite modest skill levels.

Another result is that forecast value can be further increased by following only the wet season forecasts. This is because of the relative importance of making the most of the good years compared to reducing losses in bad years. These lessons are part of learning to use the available skill from the model despite its limitations.

The first stage in assessing the value of short-term (10 day) forecasts in wheat cropping has been explored in this project, and a manuscript is in preparation (Asseng et al. 2011c, see also Appendix G). Idealised 10 day rainfall forecasts have been assessed to determine if there is likely to be value in real-world forecasts, and to provide a benchmark for using them. The results are encouraging when these 10 day idealised forecasts are used to trigger early sowing, late N application or late fungicide application to control disease. Benefits can range from $10-100/ha for early sowing, and $10-160/ha for late N and fungicide application, depending on the in-season rainfall. These benefits depend slightly on initial soil water content and strongly on in-season rainfall, and have the potential to be cumulative. This research is in its early stages but looks very promising. POAMA forecasts are not considered suitable yet for these studies because the way the model is initialised at the moment generates some initialisation shock that degrades the first 2 weeks forecast.

Finally, the value of having a frost forecast for wheat in south-west WA was investigated at three locations with rainfall ranging from medium to high (see Appendix H). Three cultivars were used; an early flowering, a medium flowering and a late flowering variety. The sowing date was delayed by 15 days if the forecast was for a high probability of frost. Initially an ideal forecast was used to see if there was a case for using POAMA model output. The results indicated that a frost forecast had little or no value compared to simply managing for average conditions. The yield penalty for delaying sowing outweighed the potential yield loss due to frost. This result depends on an assumption that frost damage was always average. If frost damage was more severe than typically observed, then a frost forecast might have some value. The results have been presented and documented in a conference paper (Farre et al. 2010).
5. Establish foundations for ongoing strategic investment in improvement of global circulation models.

This project has highlighted the value of existing POAMA forecasts to the wheat industry in WA, but it has also revealed a number of areas that need improvement (see Appendix J). It must be stressed that in a global model it is simply not possible to turn a couple of knobs to improve rainfall forecasts in a particular region. The model is a coupled global system that must simulate the important dynamical processes accurately, where some of these processes may be remote from the region of interest. The forecast system must also be initialised properly over as large a range of years as possible, and must produce an ensemble of forecasts that have a realistic and meaningful spread of results.

Perhaps the most important conclusion from this project is that the mean state of POAMA has a climatological bias that affects the rain-producing synoptic systems, and that cannot be mitigated by simple bias correction. The most promising way forward is to transition POAMA to the new ACCESS-based atmospheric model which has shown much-improved skill at weather timescales. In addition, more work is needed on improving the representation of tropical convection, and an assessment of the impact of increasing the spatial resolution (horizontally, vertically, or both) to improve topographic/coastal influences on rainfall. The move to other components of the ACCESS system, such as the ocean model, will also be of value in reducing model bias.

It is desirable to improve short-term forecasts (2-4 weeks) for tactical agricultural management. The move to the ACCESS atmospheric model will help in this regard, but it is also necessary to ensure that the ensemble generation method produces realistic variability on these short time scales. The ensemble generation method also needs to be further improved at seasonal timescales, although considerable progress has been made in the course of this project. Ideally, the model would exhibit good reliability at all timescales, that is, there is agreement in the long run between forecast probabilities and observed frequencies.

There needs to be regular and ongoing model evaluation based on a comparison between observed and model properties. These would include the mean state, synoptics, teleconnections, tropical and regional rainfall variability, ocean heat content, and many others. Of particular note is the importance of representing correctly the rain-bearing weather systems. To this end, two issues stand out: the need to output model variables at 6-hourly intervals, and the need to develop an automatic frontal recognition system. Daily model output is not adequate for the purpose of diagnosing fast-moving synoptic weather systems.

The practical application of model forecasts to agriculture often involves dividing rainfall (or other quantities) into categories. At the moment, it is not feasible to split the 27 year hindcast set into more than two groups. It would be valuable to explore more groups for additional value, and to do this requires a longer hindcast data set. Longer hindcast sets will also improve the statistical reliability of forecasts, and these are just now becoming available with POAMA-2.4.

In terms of agricultural applications, longer hindcasts will allow the assessment of forecast value when changing more than one management decision (e.g. N and sowing time combined with different initial soil water). There is more work to do on the value of frost forecasts in the event of severe frost damage, and there may be real value to obtain from forecasts of late-season heat stress. There is also more work to be done on the best use of short-term (multi-week) forecasts, particularly when the ensemble generation gives a useful forecast spread. Finally, this project has shown that there is a high potential value of a seasonal rainfall forecast in mixed crop-livestock farming systems, and there are likely to be many more mixed farming systems that could benefit from a seasonal forecast.
Output

Publications


Presentations

Alves, O. Presentation on POAMA-2 at the CLIVAR Working Group on Seasonal to Interannual Prediction, Buenos Aires.


Risbey, J.S., 2009: Climate change as if the weather mattered: Climate projections for SWWA. CSIRO Floreat science seminar.


Seasonal Prediction Update. SA Regional Office Climate Forum, June 2010.
Media
Press release through eConnect: South-west WA farmers to benefit from better climate forecasts, 8 July 2008.


WA seasonal forecasting system shows promise. Australian Farm Journal, March 2011.

GRDC Top Paddock Research Updates #12, 13 and 14 on seasonal forecasting for the northern, southern and western regions.

GRDC media release: Research probes frost impact on wheat yields, 13 January 2011.

ABC interview for country hour on Monday 17 January 2011, with Imma Farre.

List of rural paper articles from DAFWA for the frost component (see attached pdf).

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References


List of Attachments
15. Frost_media.pdf - a list of media for the DAFWA component of this project.

List of Appendices

A. Interactions with farming community
B. POAMA development
C. Climate and model diagnostics
D. Value of POAMA for N management in wheat
E. Break-even time and forecast pay-off time
F. Value of POAMA for mixed farming
G. Value of short-term rainfall forecasts
H. Frost damage
I. Value of POAMA for determining cultivar
J. Future directions
K. Project Proposal: Summary, Objectives, Outputs
Appendix A. Interactions with farming community

Meetings with farmer groups on 19 and 20 August 2009 included:
- Yuna group, 10 farmers
- Mullewa group, 10 farmers
- 15 farmers at Field Day at Shane Collins’ farm

Average farm size is 4000ha (ranging from 3000-10,000ha), short season, mainly cropping and no sheep.

What do farmers want from forecasts?

Rainfall forecast (prioritised):

1. High skill (>80%) 10-days forecast in April-May (in above mm, %probability above threshold) for canola and lupins, wheat sowing.
   - Because the size of the properties implies dry sowing with a high likelihood of follow up rains ensures earliest possible germination and increased yield potential with such a forecast. In the NAR of the WA wheat-belt, any delay in sowing results in a 30-40 kg/day decline in yield potential (Asseng et al. 2008). Starting sowing dry on a 10-day forecast would allow about 2000ha (200ha/d) being sown and then being ready for germination with the brake of the season, compared with the traditional start of sowing with the first significant rainfall in autumn (break of the season). The theoretical yield advantage could be up to 400 kg/ha (about 20% of an average yield in this region) but will vary depending on the forecast length and skill, seasons, soil types, initial soil water conditions and the technical daily sowing capacity.

2. 10-days May-June (in mm, %probability above threshold) wheat only, light soils only
   - Reasons and benefits in general as above (point 1), however, as yield potential declines faster with June sowing compared to May sowing (Asseng et al. 2008) the actual value of the forecast could be even higher than with the May sowing opportunity.

3. 10-days July to mid August (in mm, %probability above threshold) for top up N (15-20kg N = A$15-20/ha), fungicides (A$5/ha)
   - While the management decision for A$20-25/ha seems small, for an average farm in the NAR of 4000ha (up to 10,000-ha farms are common in this region) and only cropping, this can add up a significant investment decision of A$100,000 on an average farm.

4. 1-2 months in early August (above/below medium) for top up N (15-20kg N), fungicides (5$/ha) rainfall and heat forecast.
   - As most of the soils are sandy soils in the NAR, nutrients are often leached out during the highest rainfall months of June to August and crops are often N deficient by the time of flowering in August. Rainfall in average declines sharply after August and any investment of nutrients at this stage will depend on the possibility of following up rainfall in August and September. If there are following up rainfalls in August/September (like in 2008), nutrient deficient crops in August (like in 2009), not applying N fertiliser would be a lost opportunity for crop growth and grain yield, depending on the crop nutrient status, the following rainfall, temperature development (a cool spring as in 2008 and in 2009 has a higher yield potential than a hot spring with several heat events) and stored soil water at this stage.

5. 1-month forecasts early May and early June for sowing (in mm, %probability above threshold) and initial N application
   - Reasons and benefits as under point 1 with longer forecast are likely to increase the benefits of the forecast. E.g. a longer forecast would allow more area to be sown before the rainfall starts.
   - Following the desire by farmers to sow before the first significant rainfalls start in autumn, it might be also be worthwhile to investigate if and what proportion of the farm could be always sown dry without any forecast to maximise the sown area in relation with short forecasts (e.g. 10-day).
• The implications of following up rainfall after the initial rainfall (forecasted or not forecasted) might also be explored which would highlight the value of a longer forecast (e.g. 1-month) compared to a short-term forecast for a rainfall event (10-day forecast).

6. 2-month forecasts early May and early June for sowing (in mm, % probability above threshold) and initial N application
• Reasons and benefits as under point 5, but with likely higher benefits of more knowledge of the season.

7. Seasonal forecast late April and extreme forecast of very dry/very wet
• While seasonal forecasts are still desirable by farmers, the NAR farmers have realised that the skill of seasonal forecasts is currently too low to be incorporated in their seasonal decisions. Forecast skills above 80% for 2-categories are required to be useful for these farmers. A forecast of extreme dry seasons is also desirable as the base to scale back cropping or even not plant at all in this season. However, high accuracy of such a forecast would be required in order to decide not to plant. Otherwise the risk of a lost opportunity is too high even in a poor season. A low yield can still be profitable when there is a high wheat price, such as 2007.

In discussions with farmers it also became clear that they will take more risk on moist soil water conditions (i.e. after a previous fallow or significant summer rainfall or a full profile at an in-season decision point). Hence, investigations of the value of forecasting systems need to consider the forecast together with soil water status information.

Meeting with four farmers from the Southern wheat-belt from West of Katanning on 18 November 2009
An intensive discussion with four farmers in the southern wheat-belt (farms of 1200-2000ha, wheat-sheep farming, 40-60% cropping) on 18 November 2009 in Katanning indicated an interest in similar shorter-term (1-3 months) forecasts for similar and different reasons. Prioritising was less obvious in the South compared to the North and forecast needs are therefore labelled with “high”, “important” and “desirable”. The following forecast needs were indicated:

1. Farmers in the South are less interested in a 10-days forecast for dry sowing in the medium to high rainfall region, however, there is some dry sowing occurring in the low rainfall regions in the south-east (high) where the 10-day forecast could be of interest.
   • While delayed sowing also has a penalty in terms of decline in yield potential, this decline is less in the South due to the longer season, therefore there is less urgency in getting the crop in “as early as possible”. In addition, there are reasons to delay sowing in the South due to the high frost risk with early sown crops and therefore early flowering. The current research of Imma Farre and Ian Foster at DAFWA as part of this project will help to quantify and optimise the relationship with delaying sowing and losing yield potential to avoid frost risk.

2. (high) Similar to the North, there is a need for a 1-month rainfall forecast but combined with a frost forecast (due to high frost risk in the region) in early September, about a month before flowering for top up N nutrition (similar amount to the North with 15-20kg N = A$15-20/ha) + fungicides (A$5/ha).
   • Note that the phenology is delayed by 6-8 weeks due to lower mean temperatures in the South compared to the North.

3. (high) 1-2 months rainfall forecast in early May in combination with frost risk at flowering
   • Early rainfall in May with following-up rainfall (therefore May-June rainfall forecast) would allow an early sowing but has a high frost risk due to the early flowering. Therefore, such forecast of early rainfall needs to be combined with a frost risk forecast.

4. (high/important) Seasonal forecast at early May for May to October rainfall is important for decisions on canola versus wheat cropping and preparing stocking rates of sheep (selling and buying of sheep or feed) for the coming season.
• Cropping in relation to early sowing and high N input will need to include an estimate of frost risk of the season.

5. (desirable) 1-2 months rainfall forecast in early June for top up of N fertiliser application by 20-50 kg N = A$20-50/ha

• June and July are the main waterlogging months on duplex soils, which are very common in the Southern region. Waterlogging has direct (root damage) and indirect (N loss) effects on crops. If heavy waterlogging (above average rainfall) is expected for June-July, farmers would apply N before the onset of waterlogging as driving on waterlogged soil is not possible and flying on N too expensive in this region.

6. Heat was considered not to be an issue in the South, even though two heat days in October this year might have had an additional negative impact on grain filling in addition to the very low rainfall in October 2009.

References


Appendix B. POAMA development

Benchmarking POAMA-1.5

POAMA-1.5 was benchmarked against a wide range of models and statistical forecast systems at 4 sites in WA: Katanning, Nyabing, Merredin and Mullewa. A large range of skill measures were reported in Milestone report #2, and the results are presented here in a simplified fashion in terms of percent correct in 2 and 3 categories. The general conclusions remain the same.

Table B1 shows the percent correct scores in 2 categories. In the south at Katanning and Nyabing, POAMA is the best or equal best forecast system. No forecast system has significant skill in the middle of the wheat belt at Merredin, while the GESS and NINO-based statistical systems have some skill in the northern wheat belt at Mullewa.

Table B2 shows the equivalent results in 3 categories. POAMA has marginal skill at Nyabing, but is hampered by the limited number of years to span 3 categories. The GESS model does a little better with this number of categories, although the significance at Mullewa and Katanning is marginal. It has the advantage of having more than twice the number of years.

Table B1. Percent correct in 2 categories for forecasts of May-Oct seasonal rainfall. Values significant at the 95% confidence level are in bold. A random forecast has a value of 50.

<table>
<thead>
<tr>
<th>Model</th>
<th># of years</th>
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<th>Merredin</th>
<th>Mullewa</th>
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Table B2. Percent correct in 3 categories for forecasts of May-Oct seasonal rainfall. Values significant at the 95% confidence level are in bold. A random forecast has a value of 33.

<table>
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**POAMA-2 development**

After numerous hindcast experiments using various model configurations and resolutions, a final POAMA-2 has been created (version 2.4). This has been implemented operationally at BoM and is currently undergoing real-time evaluation before officially replacing POAMA-1.5. The final configuration uses the same model resolution as the current operational POAMA-1.5 but includes other enhancements. New improvements in POAMA-2 include:

- A new ocean assimilation scheme (PEODAS, Lim et al. 2010)
- A new approach for perturbing the model hindcasts and forecasts (Yin et al. 2011)
- Some changes in atmospheric boundary layer physics
- An SST bias corrected configuration
- A multi-model configuration using 3 model versions (see below for more details)
- A more comprehensive hindcast dataset back to year 1960

POAMA-2 is a pseudo multi-model as it uses three different configurations of the POAMA-2 model. These three sub-models are:

- p2.4a Standard version of the model,
- p2.4b as p2.4a but with bias-correction using the scheme developed as part of this project. It has stronger tropical SST variability which is desirable for better climate drivers’ teleconnection with Australian climate anomalies,
- p2.4c as p2.4a but with changes to the atmospheric boundary layer (similar to p15b).

Each of these model configurations produces forecasts that are complimentary. It was found beneficial to combine these into a multi-model ensemble.

Development of a flux-corrected version of POAMA-2 (p2.4b) is one of major outcomes of this project. For each configuration a 10-member hindcast set was run each month from 1960-2010. This gives a total multi-model 30-member ensemble hindcast set, the first such dataset in Australia. The hindcast set is being extended forward to the present. The complete system has been implemented operationally on the new Bureau supercomputer, and trial real-time forecasts are being produced and tested.
Performance

Assessment of performance of all hindcasts has been performed, funded by this and other projects. Below are some conclusions from comparison between POAMA-1.5 (p15b) and the different configuration of POAMA-2 i.e. p24a, p24b, and p24c. A detailed analysis is available in the technical report by Lim et al. (2010).

1) SST biases (predominantly cold biases in tropical and subtropical Pacific and Indian Oceans) have been reduced from p15b to p24a and further reduced in p24b. SST biases are about 2°C in p24a or p24c but have been reduced to less than 1°C in p24b in most places along the Pacific and Indian Ocean tropics (see left column of Figure B1).

2) The three configurations of POAMA-2 exhibit moderate differences in characteristics such as El Niño/Southern Oscillation (ENSO) behaviours. Figure B2 gives spatial patterns of the 2nd EOF mode over the Tropical Pacific for the Sep/Oct/Nov (SON) season at lead time of one month for three POAMA-2 configurations and observation. Compared with p24a and p24c, the warm centre in p24b is located further east and closer to that of the observed pattern. This suggests the flux correction has a positive impact on the model representation of the tropical Pacific SST 2nd EOF mode, which is important for tropical climate teleconnection to Australian rainfall. This has been confirmed through better Australian rainfall teleconnection with tropical Pacific SST modes in p24b than in the non flux corrected configurations (figures not shown). Anomaly correlation of the predicted Pacific SST second mode time series with observation is also higher in p24b than in p24a.

Figure B1. September SST biases (left) and precipitation biases (right) at lead time of five months initialized from May for p24a (top), p24b (middle) and p24c (bottom). POAMA-1.5 biases would be equivalent to p24c.
3) As shown above, the three POAMA-2 runs exhibit different characteristics in the simulation of the mean and variability. This justifies the multi-model ensemble (MME) approach within the POAMA-2 system. Results from the MME (i.e. combining members from p24a, p24b and p24c) indicate improved Australian rainfall skill as measured by anomaly correlation and probabilistic forecast reliability. Figure B3 shows precipitation correlation with observation for the May-September mean predictions starting on 1st May using (Figure B3a) all 30 members in POAMA-2, (Figure B3b) 10 members in p15b, and (Figure B3c) 10 members randomly chosen from the POAMA-2 set. Skill has increased by about 10% almost everywhere from p15b to the MME (Figure B3b vs. Figure B3a), and the skill gain is mainly from combining three configurations of P24 rather than from increased ensemble size (Figure B3c vs. Figure B3a). More specifically the correlation over the WA region, as defined west of 130E Australian continent, is 36%, 59%, and 54%, for p15b, 30 members MME, and 10 members MME, respectively. The improvement is also seen for rainfall probabilistic forecasts as shown by the attributes diagram for Australian rainfall being above median at one month lead for each season (Figure B4). For comparison the figure also shows the attributes diagram from the ECMWF system 3. The overall distribution of the probabilistic forecasts from p15b suggests that the forecasts tend to be overconfident. That is, forecasts of above median rainfall occur more often than observed (see for instance MAM season, left column). Figure B4 also suggests the ECMWF system exhibits similar overconfident behaviour as p15b. However, this problem has been significantly reduced with the MME approach (Figure B4, top two rows).

4) Improvement from using the MME at regional scales is likely. In the SWWA region high hit-rates of 2 out of 3 forecasts correct for above/below median rainfall is seen for multiple sites (e.g. Katanning and Nyabing) for multiple forecast averaging periods. However, the statistical significance of results at the grid-point scale or less is questionable.

5) The ensemble spread in rainfall appears larger in the tropics, mainly due to p24b, which is a desirable feature.
Issues

Rainfall forecast skill is generally comparable among the three POAMA-2 configurations, suggesting biases other than mean SST bias are limiting Australian rainfall skill. One possible candidate is mean rainfall biases in the tropics as this indicates deficiencies in the simulation of the tropical atmosphere, particularly too little rainfall in tropical Indian Ocean in all three configurations (see right column of Figure B1). This suggests that further skill improvement over SWWA requires reducing the tropical mean rainfall biases in regions such as the tropical eastern Indian Ocean where SST forcing through convection processes excite teleconnection influences on rainfall over SWWA. This knowledge will be used in developing the future ACCESS-based POAMA system.

From a model/forecast improvement perspective, priorities for the extension of the project into years 4 and 5 can be related to evaluation of the atmospheric component of the next version POAMA-3. This is where we believe improvements need to be made to improve the model tropical simulation and its teleconnection to SWWA climate. POAMA-3 will use the ACCESS-based atmospheric model and priority should be given to evaluating how this model simulates the tropical and regional rainfall variability compared with POAMA-2. In particular, progress can rapidly be made in investigating the impact of increasing resolution. This would help guide the best configuration for POAMA-3 that would give improved skill in SWWA. It would also provide a cost/benefit analysis for increasing model resolution, which is always being limited by supercomputing resources. For example, POAMA-2 has a grid spacing of approximately 250 km over WA. The standard UK Met Office climate model presently being tested for POAMA-3 has a resolution of approximately 150 km. However the Met Office has investigated increased resolution as high as 70 km and shown that increasing resolution leads to improvements in model simulation, although this has not been evaluated over Australia. A 70km resolution model would be approximately ten times more expensive than a 150 km resolution model. The benefits of increasing resolution have not been evaluated and the best resolution/cost option for POAMA-3 has not been investigated.

Key results have been reported in two manuscripts that are attached to this report (Lim et al. 2010; Yin et al. 2011).
Figure B4. Attributes diagram of POAMA p15b (top), p24 MME (middle) and ECMWF (bottom) prediction of above median rainfall for each season at lead one month, over all grid points of Australia. The diagonal line indicates perfect reliability. Forecasts falling in the grey areas are considered to be reliable forecasts as they correctly indicate the occurrence/non-occurrence of exceedance of median rainfall.

Appendix C. Climate and model diagnostics

Synoptic Analysis and Climatology

The synoptic analysis has now been extended back to 1965 and with the inclusion of the 2009 growing season, a further seventeen years of data have been added to the analysis set since the previous report. Overall, the relative proportions of rain contributed by frontal systems and the mid-tropospheric system known as the cutoff low have not changed significantly. According to this analysis, frontal systems contribute approximately one half of the growing season rainfall in the Central Wheat Belt (CWB) while cutoff lows contribute about one third. Importantly, the correlation between cutoff low rain and frontal rain in the growing season is very low (r = -0.19, n = 45), indicating that the two most important rain producing systems act largely independently of each other. Extending the synoptic analysis beyond the confines of the CWB reveals that the proportion of rainfall contributed by cutoff lows increases inland and northwards from the high rainfall region in the southwest corner of WA while the frontal component declines.

In Figure C1, the proportions of growing season rainfall contributed by various synoptic systems are displayed for the northern centre of Mullewa, the southern centre of Katanning, an 8-station average for the Central Wheat Belt (CWB), Perth Airport and the western wheat belt town of York. In each case, frontal systems produce the highest percentage of rain but the proportion varies from as low as 43% at Mullewa to an average of 50% for the CWB and to 54% at Katanning and York. Near the coast, Perth Airport receives about 58% of its growing season rain from frontal systems. The proportion of rain due to cutoff lows is slightly above 30% except in the far south and west where it declines to 27% or less. Figure C1 also reveals that the proportion of rainfall associated with troughs in the easterlies is about 10% but tends to be a little higher in the north and lower in the south.
Figure C1. The percentage contribution of synoptic types to growing season (April to October) rainfall for an 8-station average in the Central Wheat Belt and for the separate locations of Mullewa, Katanning, York and Perth Airport.

The percentage of rainfall contributed by cutoff lows is highest in autumn and spring and exceeds the frontal contribution in April and October. At the northern station of Mullewa the percentage of rainfall contributed by cutoff lows is also higher in September (Figure C2).

Figure C3 shows a time series of the total amount of rain in the central wheat belt along with the contributions from frontal systems, cutoff systems, and airstreams. With the extension of the synoptic classification back to 1966, fluctuations from decade to decade in rainfall amount are apparent, though there is no strong trend over the entire time period since then. The period in the mid-1970s shows a marked increase in rainfall which is contributed by both fronts and cutoff lows. There is however a downward trend in rainfall in the region since the mid 1990's. As is apparent in the figure, that trend is mostly due to a reduction in rainfall from cutoff lows, and only weakly contributed by frontal systems.

Figure C2. The percentage contribution of the synoptic types, frontal systems and cutoff lows, to monthly rainfall at Mullewa in the north of the grain growing region.
Figure C3. The time series of the total amount of rain in the central wheat belt along with the contributions from frontal systems, cutoff systems, and airstreams from various directions.

In Figure C4 we show time series of the number of cutoff and frontal systems over the period and of the amount of rain per cutoff and per frontal system over the period. The top two panels show that there has not been much change in either the number of cutoffs or fronts during the period of rainfall decline since 1995. Rather, the decline is due primarily to a reduction in the amount of rain per system, as evident in the bottom two panels for the period since 1995.

Figure C4. The time series of the number of cutoff and frontal systems and of the amount of rain per cutoff and per frontal system over the period (1966-2008).

The results of this work have been reported in a manuscript attached to this report (Pook et al. 2011).
Blocking

In south-east Australia, it has already been established that atmospheric blocking is related to growing season (Apr-Oct) rainfall (Risbey et al. 2009). The dynamical mechanism is thought to be related to the generation of cutoff lows, which are known to produce half the rainfall in these months. It is also speculated that blocking acts to slow the west to east propagation of cutoff lows, thus allowing them to produce more rain in a particular location.

In south-west Australia, the decline in rain from cutoff systems is likely associated with changes in blocking in a similar way. Although cutoff lows are responsible for a smaller fraction of the rainfall (one third) in southwest Australia, this is still a significant fraction. More importantly, they are the synoptic type that is associated with the majority of the rainfall decline. In addition, cutoff lows are known to be more important in the northern part of the central wheat belt, especially in autumn and spring.

Figure C5 shows a time series of the observed blocking index at 120E. Blocking is measured here by the simple Bureau of Meteorology blocking index, BI (Pook and Gibson 1999). Although other more sophisticated measures are available (e.g. Tibaldi et al. 1994), BI has been developed specifically for use in the Australian region. The reduction in the index is consistent with a reduction in blocking and cutoff rainfall in southwest WA. Having identified the key roles of cutoff systems and blocks in diagnosing rainfall in southwest WA, we further need to examine the factors controlling blocking in the region. This is part of ongoing research.

Figure C5 shows a time series of the observed blocking index at 120E. Blocking is measured here by the simple Bureau of Meteorology blocking index, BI (Pook and Gibson 1999). Although other more sophisticated measures are available (e.g. Tibaldi et al. 1994), BI has been developed specifically for use in the Australian region. The reduction in the index is consistent with a reduction in blocking and cutoff rainfall in southwest WA. Having identified the key roles of cutoff systems and blocks in diagnosing rainfall in southwest WA, we further need to examine the factors controlling blocking in the region. This is part of ongoing research.

![Blocking Index Time Series](image)

**Figure C5.** The time series of the mean blocking index for Apr-Oct at 120E.

We also need to examine the ability of POAMA to capture blocking in southwest WA. It is vitally important that climate models are capable of reproducing accurately cutoff lows and atmospheric blocking.

The blocking index in POAMA is shown in Figure C6 as a function of lead time and time of year. The value is the blocking index at 120E averaged over all 10 ensemble members. A lead time of zero corresponds to the observed blocking index, so that the evolution of POAMA’s blocking climatology as a function of lead time is obtained by choosing a month and moving vertically up the diagram. For example, blocking is a maximum of about -1.2 in June and decreases below -10 at a lead time of 4. In other words, a forecast for June that starts in February will, on average, have a blocking value about 9 below that observed in June.
Figure C6. POAMA-1.5 blocking at 120°E as a function of lead time and month.

Similar behaviour has been observed at other longitudes, indicating that POAMA has difficulty in representing blocking accurately for lead times longer than a few months.

A related diagnostic is the upper level wind at the height of the sub-tropical jet, typically 200hPa. The observations show a split in the jet in the Australian region, with a branch forming to the south of the main jet at 20-25S. This split is associated with atmospheric blocking. Figure C7 shows the observed (NCEP) and POAMA zonal wind at 200hPa for May June, July and August. The POAMA start time is always May, and the wind field is the ensemble mean.

It is clear from Figure C7 that the observed upper level wind maintains a split in the southern Tasman Sea. The subtropical jet occurs at a latitude of 25-30S, and the polar jet occurs at about 60S. While POAMA has a similar split at lead time 1 month (i.e. in the first month after the start time), it starts to lose intensity and move eastwards after that.

Figure C8 shows the sea-level pressure equivalent of Figure C7. In May we see that POAMA agrees well with observations, as it should close to the initialisation time. However, as the lead time increases, the meridional pressure gradient over southern Australia (both east and west) becomes larger than observed, and the contours become too zonal. Both these features act to propagate weather systems too fast in the model; the cutoff lows will transit the south of Australia too fast to produce realistic rainfall. This is an alternative way to view the lack of blocking in POAMA at lead times beyond a few months.

It would be ideal to be able to diagnose cutoff lows in POAMA. Other climate models show an inability to represent the correct frequency of cutoff lows, and this may be related to problems with blocking. The existing POAMA data is not suitable for this purpose yet. The 1000hPa height field is definitely required, and it would also be better to have 6-hourly data rather than daily. The former is easily obtained, the latter is not. The need for an automatic frontal system recognition scheme to complement the cutoff low scheme was flagged. This is a substantial undertaking, and might form part of a follow-on project.
Figure C7. Observed (NCEP – left column) and POAMA (right column) 200hPa zonal wind in m/s. The top row is May, second row is June etc. The POAMA start time is always May, and the wind field is the ensemble mean.
Figure C8. Observed (NCEP – left column) and POAMA (right column) sea-level pressure in hPa. The top row is May, second row is June etc. The POAMA start time is always May, and the wind field is the ensemble mean.

**POAMA-1.5 rainfall forecast skill**

**Background**

Australia’s seasonal climate forecast model is called POAMA (Predictive Ocean Atmosphere Model for Australia). It is run by the Bureau of Meteorology in both operational and experimental modes. Operational output comprises SST plumes for three Pacific Ocean indices (Nino3, Nino3.4 and Nino4), and for the Indian Ocean Dipole index. SST anomaly forecasts are also available up to 7 months ahead (see [http://www.bom.gov.au/climate/coupled_model/poama.shtml](http://www.bom.gov.au/climate/coupled_model/poama.shtml)).

Experimental output from POAMA is available at [http://poama.bom.gov.au/experimental/poama15/r_gen.htm](http://poama.bom.gov.au/experimental/poama15/r_gen.htm), and contains much more information, including rainfall forecasts. There is also an OpenDAP server where all the model output at daily or
monthly timescales can be obtained. As of March 2011, the operational version of POAMA is about to be upgraded from 1.5 to 2.4.

The current operational version of the model runs once a day, forecasting up to 9 months ahead. Ensemble forecasts are obtained by averaging as many of these daily runs as required. These forecasts have been running with POAMA-1.5 for less than a year. However, a hindcast data set is available spanning the years 1980 to 2006, from which the skill and value of this version of the model can be assessed. The ensemble structure of this data set is different from the operational setup. The hindcast data set comprises ten forecasts initialised at the start of every month from January 1980 to December 2006. These forecasts also extend to 9 months. The model output used here is a simple average of the ten ensemble members.

The spatial resolution of POAMA is relatively coarse, being exactly 2.5 degrees in longitude, and approximately 2.5 degrees in latitude. The temporal resolution of the model about 15 minutes during the mode run, but the output is only stored at a daily timescale. The data used here is averaged to monthly values.

**Validation Data**

Rainfall data for validating the model is gridded monthly rainfall on a 0.5 degree grid. The data is a Bureau version of the SILO rainfall product, informally called BILO, and is obtained through the CSIRO EOC web site. The SILO product is no longer being updated. The original data set is produced on a 0.05 degree grid, and this has been summed (rather than decimated) onto a 0.5 degree grid because of the high spatial variability of rainfall. This facilitates comparison with the coarse spatial resolution of the POAMA model.

**Model/Data Comparison**

We focus on the southern winter growing season of May to October. Although rain earlier in the year can be of benefit if stored in the soil, the May-Oct period is the main time for rainfall of benefit to grain crops in the southern half of Australia. The May-Oct rainfall total for Australia from the BILO 0.5 degree data is shown in Figure C9. It can be seen that rainfall is confined to the southern and south-eastern parts of the continent, with the highest values occurring near coasts and topography. Maximum values reach to almost 1800mm in the west of Tasmania, but the contour limits are reduced to show detail elsewhere.

![Figure C9. Observed May-Oct rainfall sum from BILO data on a 0.5 degree grid.](image)
POAMA rainfall predicted for May-Oct from forecasts starting on the 1 May is shown in Figure C10. While showing qualitative agreement on a broad scale, the high rainfall amounts near coasts and topography are clearly missing. This is not surprising considering the relatively coarse grid of the model. In addition, the northward extension of the moderate rainfall regions near the west and east coasts is less than observed.

The linear correlation coefficient, $r$, between the observed and modelled rainfall is shown in Figure C11. The model appears to have the greatest skill by this measure in southeast Queensland, where $r$ exceeds 0.6 in places. In southwest Western Australia, the correlation is between 0.3 and 0.4. Very similar results are obtained if the 2.5 degree BILO data are used.
Another measure of skill is percent correct in n categories. This measure is closer to the way a forecast might be used in practice in agriculture. Muller et al. (2008) have shown that there is little value to be gained from using rainfall in more than about 3 categories, and that 2 categories is quite adequate. The percent correct in 2 categories is shown in Figure C12, while percent correct in 3 categories is shown in Figure C13. A random forecast will score 50% in 2 categories, and 33% in 3 categories.

In southwest WA, POAMA scores 70% correct in 2 categories, which is considerably better than random. POAMA also scores 44% correct in 3 categories, again better than random. So while the skill of POAMA at predicting rainfall in SWWA is lower than might be desired, there might well be enough skill to be useful in an agricultural context.

![Figure C12. Percent correct in 2 categories for May-Oct rainfall from forecasts starting on 1 May.](image)

![Figure C13. Percent correct in 3 categories for May-Oct rainfall from forecasts starting on 1 May.](image)
Katanning Rainfall

Katanning lies in the southern wheat growing region of SWWA at 117.56°E, 33.69°S. The mean May-Oct rainfall over the period 1889-2007 is 359mm (see Figure C14). The data is from the SILO patch-point data base. Using a linear fit to the data, we see that the rainfall has been decreasing very gradually at a rate of 0.235mm per year (red curve). Alternatively, a single break point can be found by breaking the data into two segments and minimizing the chance that the two individual segment mean values are the same. This is shown in Figure C14 by the green line, and is a rainfall decrease of 45mm in 1975.

![Katanning May-Oct rainfall](image)

**Figure C14.** Katanning May-Oct rainfall from SILO data. Red curve is the best linear fit, green curve is the most significant single jump.

The nearest POAMA model grid point to Katanning is fortuitously very close; at 117.5°E, 33.52°S. However, it must be remembered that a model grid point covers an area that is 2.5 degrees square, whereas the BILO data base used here is on a 0.5 degree grid. The correlation between the Katanning SILO station data and the 0.5 degree gridded data at 117.5°E, 33.5°S is 0.95. The correlation between the station data and the 2.5 degree data is 0.91. Note that both BILO gridded products have been averaged to ensure that Katanning lies almost exactly on one grid point. This also ensures that the 2.5 degree BILO data and the POAMA grid agree very closely in the SWWA region.

The correlation between the Katanning station data and the nearest POAMA grid point is 0.34. If the nearest BILO grid point is used, rather than the station data, the correlation drops slightly (probably not significantly) to 0.32. The actual rainfall values from POAMA have a mean slightly less than half the observed mean (168mm vs. 352mm).

The chocolate wheels (contingency table) for the POAMA forecast of Katanning rainfall in May-Oct starting on 1 May are given in Figure C15 (for 2 categories) and Figure C16 (for 3 categories). We use the BILO 2.5 degree gridded product rather than station data, even though for this case the station data give slightly better results. Elsewhere this may not be true, and it is a fairer comparison to use similarly-averaged data.
It seems that, particularly in 2 categories, there may be some useful skill in the forecast. In 3 categories there may also be some skill, but it is less clear whether it will have any substantial value.

So far we have only explored forecasts starting in May for May-Oct rainfall. The skill was 0.32 (predicting the BILO 2.5 degree gridded rainfall centred on Katanning). If the forecast is started in Feb, the skill is 0.2, starting in Mar the skill is 0.02, and starting in Apr the skill is 0.24. None of these
values are significant at the 80% level, and so forecasts at these lead times are not expected to be useful or to give much value.

Another aspect of forecasts to explore is the forecast period. So far we have only looked at forecasting the 6 month period May-Oct. The following table shows the skill of forecasts starting in May for different periods. These values are fairly similar, although perhaps adding the month of July has caused a drop in skill.

<table>
<thead>
<tr>
<th>Period (months)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skill (r)</td>
<td>0.27</td>
<td>0.38</td>
<td>0.20</td>
<td>0.36</td>
<td>0.38</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Next we look at the skill of forecasting 3 month periods starting at different times of the year. The following table shows the skill of forecasts starting in different months for 3 month periods starting in that month. Again, moving to July causes a decrease in skill.

<table>
<thead>
<tr>
<th>Month</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skill (r)</td>
<td>-0.16</td>
<td>-0.15</td>
<td>0.41</td>
<td>0.20</td>
<td>0.56</td>
<td>0.27</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Finally, we explore the skill of one month forecasts in different months, as shown in the following table. There is a great deal of variation here, including a substantial drop in skill when moving from May to July. The month of July clearly needs further exploration to ascertain why the skill at forecasting this month drops.

<table>
<thead>
<tr>
<th>Month</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skill (r)</td>
<td>0.27</td>
<td>0.52</td>
<td>0.09</td>
<td>0.16</td>
<td>0.44</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

There is some spatial variation of skill, and this can be seen in Figure 3. The following table shows the variation in skill and hit rate (percent correct in 2 categories) at Katanning and in the neighbouring model grid boxes (N.B. there are no land cells to the south of Katanning). The shaded cell is Katanning itself. These numbers are for May forecasts of May-Oct rainfall. Despite the variation, there is enough consistency to think that the Katanning results are not spurious.

<table>
<thead>
<tr>
<th>Mullewa Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mullewa lies in the northern wheat growing region of SWWA at 115.51°E, 28.54°S. The mean May-Oct rainfall over the period 1889-2007 is 249mm (see Figure 17). Using a linear fit to the data, we see that the rainfall has been decreasing gradually at a rate of 0.411mm per year (red curve). Alternatively, a single break point can be found by breaking the data into two segments and minimizing the chance that the two individual segment mean values are the same. This is shown in Figure C17 by the green line, and is a rainfall decrease of 88mm in the year 2000.</td>
</tr>
</tbody>
</table>
Figure C17. Mullewa May-Oct rainfall from SILO data. Red curve is the best linear fit, green curve is the most significant single jump.

The nearest POAMA model grid point to Mullewa is reasonably close at 115.0°E, 28.55°S. However, it must be remembered that a model grid point covers an area that is 2.5 degrees square, whereas the BILO rainfall data base used here is on a 0.5 degree grid. The correlation between the Mullewa SILO station data and the 0.5 degree gridded data at 115.5°E, 28.5°S is 0.97 over 1900-2007. The correlation between the station data and the 2.5 degree data is 0.91.

The correlation between the Mullewa station data and the nearest POAMA grid point is 0.09, which is not significant. If the nearest BILO grid point is used, rather than the station data, the correlation is 0.08. The actual rainfall values from POAMA have a mean that is one quarter of the observed mean (58mm vs. 235mm).

The chocolate wheels (contingency table) for the POAMA forecast of Mullewa rainfall in May-Oct starting on 1 May are given in Figure C18 (for 2 categories) and Figure C19 (for 3 categories). We use the BILO 2.5 degree gridded product rather than Mullewa station data, so that the spatial averaging matches that of the model.

It seems that POAMA-1.5 has difficulty demonstrating any skill at Mullewa in 2 or 3 categories. It is doubtful whether the forecast will have any substantial value.
Merredin Rainfall
Merredin lies in the central wheat growing region of SWWA at 118.16°E, 31.28°S. The mean May-Oct rainfall over the period 1903-2007 is 226mm (see Figure C20). Using a linear fit to the data, we see that the rainfall has been decreasing gradually at a rate of 0.28mm per year (red curve). Alternatively, a single break point can be found by breaking the data into two segments and minimizing the chance that the two individual segment mean values are the same. This is shown in...
Figure C20 by the green line, and is a rainfall decrease of 27mm in the year 1974 (98% confidence). Note the decreased rainfall variability compared to Katanning and Mullewa.

![Merredin May-Oct rainfall](image)

**Figure C20.** Merredin May-Oct rainfall from SILO data. Red curve is the best linear fit, green curve is the most significant single jump.

The nearest POAMA model grid point to Merredin is reasonably close at 117.5°E, 31.03°S. This is one grid point north of Katanning, and one to the southeast of Mullewa. It must be remembered that a model grid point covers an area that is 2.5 degrees square, whereas the BILO rainfall data base used here is on a 0.5 degree grid. The correlation between the Mullewa SILO station data and the 0.5 degree gridded data at 118.0°E, 31.5°S is 0.93 over 1903-2007. The correlation between the station data and the 2.5 degree data is 0.88.

The correlation between the Merredin station data and the nearest POAMA grid point is 0.38, which is significant. If the nearest BILO 2.5 grid point is used, rather than the station data, the correlation is 0.32. The actual rainfall values from POAMA have a mean that is one half of the observed mean (103mm vs. 211mm).

The chocolate wheels (contingency table) for the POAMA forecast of Merredin rainfall in May-Oct starting on 1 May are given in Figure C21 (for 2 categories) and Figure C22 (for 3 categories). We use the BILO 2.5 degree gridded product rather than Merredin station data, so that the spatial averaging matches that of the model.

It seems that POAMA shows the same skill at Merredin as at Katanning, so there should be substantial value here.

**Summary**

The skill of POAMA-1.5 at forecasting May-Oct rainfall starting in May has considerable spatial variation over Australia, with maximum values in SE Queensland. The skill at Katanning in the southern wheat belt of WA is somewhat lower (r=0.32) but is never-the-less valuable when taken through to on-farm management decisions and gross margin. This is mainly because the hit rate (percent correct in 2 categories) is 70%, which is significantly more than the chance value of 50%. Merredin, in the central wheat belt, shows much the same behaviour. On the other hand, the skill and hit rate in the northern wheat belt at Mullewa is sufficiently low to not be useful or valuable.
There is also some temporal variability in skill, with July in particular emerging as a low skill month requiring further study. This is of particular relevance when considering in-season forecasts. It is hoped that these diagnostics can help point to further improvements in POAMA.

Figure C21. Chocolate wheels for Merredin gridded May-Oct rainfall and POAMA forecast starting on 1 May for 2 categories.

Figure C22. Chocolate wheels for Merredin gridded May-Oct rainfall and POAMA forecast starting on 1 May for 3 categories.
POAMA-2 rainfall skill

Changes explored here are the new BILO version 3 rainfall data set (rather than the old version used previously, which is slightly prior to version 1), and the various POAMA-2.4 rainfall forecasts (a, b and c).

The new version 3 rainfall (Jones et al. 2009) correlates with version 1 at greater than 0.95 nearly everywhere (May-Oct sum for 1980-2006), and over 0.99 in our areas of interest in SWWA. There are lower correlations in central outback WA (down to 0.62), due to sparse observations and differences in interpolation techniques.

The Katanning grid point rainfall from version 1 is correlated with the POAMA-1.5 forecast from May at 0.34 (was 0.32 using the original rainfall). This doesn’t change using version 3 of the rainfall. Katanning is the grid point to the right of the bottom left coloured cell.

Figure C23. Spatial correlation between various POAMA runs starting on 1 May and BILO observed rainfall data set for the period May-Oct. This is a LT0 forecast. The particular POMA run is given in the individual plot titles. POAMA-2.4ave is a simple average of POAMA-2.4a, b and c.

- 38 -
POAMA-2.4a is correlated at 0.23, 2.4b at 0.15 and 2.4c at 0.14. If the rainfall is simply averaged over the three versions, the correlation is 0.18. Figure C23 show the spatial pattern of correlation with BILO observations over the whole continent for the different model configurations.

Although it appears that POAMA-2.4 has degraded the rainfall skill at Katanning for May-Oct, if we look at the skill of forecasting winter (JJA) rainfall from a 1 May start, the skill has increased from 0.27 to 0.37. Furthermore, the skill has increased over much of Western Australia at the same time (see Figure C24). These results agree with those of Sally Langford (CAWCR, pers. comm.), although she used Brier skill scores while these plots use correlation r.

Figure C24. Spatial correlation for a one month lead forecast, starting on 1 May, for JJA rainfall. Models are POAMA-1.5 and POAMA-2.4ave.

Looking at the reason for this, the LT0 (lead time zero) forecast for May has decreased substantially from 0.31 in POAMA-1.5 to 0.03 in POAMA-2.4ave. So the short term forecast is much worse. However, the forecast for Sep-Oct from a 1 May start has increased skill: from -0.15 up to 0.24

The forecast for Jun-Oct from a 1 May start has increased from 0.20 to 0.33. The May-Oct forecast skill from a 1 May start has decreased from 0.34 to 0.18 as indicated previously. It would appear that the low skill of POAMA-2.4ave in the first month is having a big impact on its seasonal forecast skill.

Let’s now look at the skill more generally, as a function of lead time and forecast length, for different model runs at Katanning (and one at Mullewa in the north). Note that the numbers are a little bit different to the individual ones quoted above. This is because the above figures are generated by averaging the fine grid rainfall to the coarse POAMA grid in a routine called ave2grid that is not very smart about the way it handles partial grid boxes at the edges. In Figure C25, the Katanning rainfall is averaged to the POAMA grid accurately.

The top left panel of Figure C25 shows that POAMA-1.5 is quite good at LT0 for most forecast lengths. Longer lead times are generally less skilful except for LT3 which is a mystery. The next 4 panels are for POAMA-2.4 a, b and c, and the average of these. They show that POAMA-2.4 is not so good at LT0, particularly for short lead times, but that LT1, LT2 and even LT3 are pretty good for most lead times. Finally, the last panel shows that POAMA-1.5 is not very good at Mullewa in the northern wheat belt, although LT2 shows some promise for longer forecasts.
Ensemble Spread

Ensemble forecasts involve starting the coupled model from a range of slightly different initial conditions to assess the range of possible outcomes given the uncertainty about the initial state. In the case of POAMA, the atmospheric state is altered by displacing the initial time by multiples of 6 hours until an ensemble of 10 members is obtained. The average of the 10 ensemble members is generally reported as the most likely outcome. There is evidence that the ensemble mean is more accurate, on average, than any single ensemble member. There is also evidence from numerical weather prediction studies that the ensemble spread is a useful estimate of the forecast skill. However, for the longer timescales involved in seasonal forecasting, it is not clear if this will still be true. It is known that the method POAMA uses to generate the ensemble members is not ideal, and clearly this area requires substantial further work in a separate project.

As a first step in exploring the use of ensemble hindcasts (retrospective forecasts), the ensemble-scaled rainfall error was calculated. To compute this, the rainfall error (ensemble mean minus observations) is divided by the ensemble standard deviation. Ideally, this value would be unity, indicating that the ensemble spread is a good estimate of the average hindcast rainfall prediction error. Over much of southern Australia, this value was close to 1 for a one month lead time (see Figure C26). At Katanning it was 1.7, but at Mullewa the value was 3.8. At longer lead times, this value increased (see Figure C27). For the May-Oct period, it was 3 at Katanning and 16 at Mullewa.

Since useful skill has been obtained at Katanning (the southern location), and there is no useful skill at Mullewa (the northern location), it could be argued that the ensemble spread is indeed providing some sort of rough estimate of overall forecast skill.
Figure C26. Ensemble-scaled rainfall error for POAMA-1.5 for a May start and lead time of one month. The ideal value is one. Katanning is 1.7 and Mullewa is 3.8.

Figure C27. Ensemble-scaled rainfall error for POAMA for a May start and a forecast for May-Oct. The ideal value is one. Katanning is 3 and Mullewa is 16.

References


Appendix D. Value of POAMA for N management in wheat

Seasonal rainfall forecasts from the coupled ocean-atmosphere global circulation model POAMA were skill tested and employed for N fertiliser decision making in the Western Australian wheat-belt. The POAMA seasonal rainfall forecast showed significant skill in forecasting rainfall season types in southern regions of the Western Australian wheat-belt. This skill resulted in about A$50 ha\(^{-1}\) of additional benefits when used in N management decisions in wheat cropping (Figure D1). However, such a forecast should not be used without considering other systems knowledge available to farmers. Combining a forecast with systems information such as initial soil water conditions can be crucial in obtaining value from a forecast. Another important factor to consider is the realistic risk behaviour of farmers, where the return from additional fertiliser is expected to exceed the cost by a factor of two or more. Finally, variations in fertiliser cost and wheat prices are critical in determining the benefits of using a forecast system for management decisions in agriculture. Using a forecast for only the wet season-type can further increase a forecast value because the additional gains in wet seasons are often higher than the savings from reduced fertiliser in dry seasons. However, the skill of POAMA forecasts was statistically insignificant in central and northern parts of the Western Australian wheat-belt and therefore had no value in these areas.

![Figure D1](image)

Figure D1. Simulated average benefits (A$ ha\(^{-1}\)) of using a 2-category POAMA seasonal rainfall (May-October) forecast for N fertiliser management compared with not using a seasonal forecast for four main soils (average of clay, duplex, deep loamy sand and loamy acid sandy soils) for dry (open bars) and wet (filled bars) initial soil water conditions at the start of the season in May for locations with statistically significant POAMA-2-category seasonal rainfall forecasts in the Western Australian wheat-belt. Symbols show benefits from following the ‘above median rainfall’ POAMA forecast only (i.e. change N fertiliser for ‘above median rainfall’ only and no change in fertiliser applications for ‘below median rainfall’ forecasts). Relative benefits from using POAMA forecasts are shown next to bars and symbols. Wheat price at A$200 t\(^{-1}\), N fertiliser cost at A$1 kg\(^{-1}\) N and a profit target of A$2 per each 1A$ invested in N fertiliser.

While these results used the average of POAMA forecasts based on 10 ensembles, using the spread of the individual ensembles could increase the reliance of a forecast in a specific year. For example, if at least 80% of the ensembles predicted an above median rainfall at Katanning (6 times between 1980-2006), it turned out in each of these years to become an above medium rainfall year, (4 of the 6 times at Nyabing) (Figure D2). Hence, the likelihood of a correct forecast in a specific year increases with the shift in ensemble spread towards predicted wet seasons (less so for predicted dry seasons (Figure D3).

The results of this work have been reported in a manuscript attached to this report (Asseng et al. 2011b).
Figure D2. - Simulated gross margins (A$ ha$^{-1}$) with using a 2-category seasonal rainfall (May-October) POAMA forecast for N fertiliser management (grey bars) compared with not using a seasonal forecast (black bars). Years with a wrong POAMA seasonal rainfall forecasts are indicated with a cross and years with observed below median seasonal rainfall forecasts are indicated with a triangle in the lower part of the figure. Lower graphs show the percentage of POAMA forecast ensembles predicting above median rainfall seasons. Simulations are for an initially dry (at start of season) clay soil at Katanning (left) Nyabing (right) in the Western Australian wheat-belt. Wheat price at A$200 t^{-1}$, N fertiliser cost at A$1 kg^{-1}$ N and a profit target of A$2 per each 1A$ invested in N fertiliser.
Figure D3. Simulated extra gross margins (A$ ha$^{-1}$) with using a 2-category seasonal rainfall (May-October) POAMA forecast for N fertiliser management versus the percentage of ensembles forecasts above median rainfall seasons. Simulations are for an initially dry (at start of season) clay soil at Katanning (top) Nyabing (bottom) in the Western Australian wheat-belt. Wheat price at A$200 t^{-1}$, N fertiliser cost at A$1 kg^{-1} N$ and a profit target of A$2 per each 1A$ invested in N fertiliser.

Appendix E. Break-even time and forecast pay-off time

One of the key findings in this project is that a seasonal rainfall forecast is much more valuable when used together with a realistic N application strategy than with an idealised N strategy (Asseng et al. 2011a, attached as a pdf). An idealised N strategy is where a farmer keeps adding N until his/her gross margin no longer increases. This means that the last $1 of N applied is gaining just 1c (say). When the value of a forecast is assessed under this idealised N strategy, there is little additional benefit to gain from a forecast because the farming system is already being pushed quite hard. However, our conversations with farmers found that they like to be much more conservative when applying N, typically only adding another $1 of N when it is likely to return $2 in the long run.

The reason for this conservative behaviour is revealed by our modelling of the farming system. The idealised strategy is risky because there is an increased chance of a big loss, and an increased chance of several loss years in a row. A single loss year might have an impact on subsequent years because the farmer has insufficient funds to plant or fertilise as much as desired. Several bad years in a row risks losing the farm. Figure E1 shows modelled gross margins for both N strategies on a typical farm on clay soil at Nyabing. It is clear that individual year losses are much higher using the risky N strategy, and in this particular sequence of years, the first 3 years are a loss, which might cause a loss of the farm.
Figure E1. Yearly gross margins on a simulated wheat farm on clay soil at Nyabing for two N strategies. The risk averse strategy applies $1 of N only if a $2 return is expected. The maximise GM strategy applies N so long as the gross margin increases, no matter how small the increment.

The issue of risk can be examined more formally by calculating the number of years it would take a farm to break-even using the two strategies. This is done using the gross margin data in Figure E1 and a Monte Carlo method with a confidence level of 95% (although other levels could easily be used). A farmer using the idealised (maximise GM) N strategy could be 95% sure of breaking-even after 6 years; the equivalent time for a conservative farmer is just 3 years (see Figure E2).

Therefore, although a farmer using the idealised strategy might make more money in the long run, he/she is unlikely in practice to survive financially in the long run.

Figure E2. 95% confidence intervals on gross margin for the conservative (risk averse) and idealised (maximise GM) N strategies as a function of the number of years of farming.
The question is now whether a POAMA rainfall forecast can help a conservative farmer be more profitable. As described in Asseng et al. (2011a), the POAMA rainfall forecast at Nyabing is used in two categories (above/below median) to determine a separate N application amount for each category using the same conservative $1 for $2 rule. The POAMA forecast is right 19 out of 27 years, and this is clearly enough to make considerably more money in the good years while having little negative effect. (see Figure E3).

![Figure E3](image-url)

**Figure E3.** Yearly gross margins at Nyabing on a clay soil with (red) and without (black) a forecast using the conservative N strategy of $1 for $2. Triangles indicate below median years, and crosses indicate a wrong forecast.

The break-even time for a farmer using a POAMA forecast can be calculated in the same way as before, and then this time compared to a farmer not using a forecast. Furthermore, the number of years that a farmer would need to use a POAMA forecast in order to be 95% certain that it would pay-off can also be calculated. The break-even time goes up from 3 to 4 years because a forecast allows the farmer to add more N, which is a little riskier, although the long-term profit is much greater. The pay-off time for a forecast at the 95% confidence level is 7 years (Figure E4). At the 80% confidence level, the pay-off time is 3 years (Figure E5). Note that a perfect forecast always performs as well as or better than not using a forecast.
Figure E4. Gross margin as a function of number of years of farming both with and without a forecast for the conservative N strategy. The results for a perfect forecast are shown in grey. The 95% confidence level has been used.

Figure E5. Same as Figure E4 but at the 80% confidence level.

The long-term annual income for a farmer sowing 2500 ha is shown in Table E1 for three cases; not using a forecast, using POAMA’s forecast and using a perfect forecast. The results for the two N strategies are also shown. It can be seen that a POAMA forecast is more valuable to a farmer who uses a conservative N strategy. In addition, the forecast helps make a farmer almost as much as if the farmer used a risky N strategy, but with a break-even time of 4 years rather than 6 years, hence reducing the risk.
Table E1. Long-term annual gross margin for a farmer sowing 2500 ha on a clay soil at Nyabing. Forecast efficacy is the percentage of the value of a perfect forecast that a POAMA forecast achieves.

<table>
<thead>
<tr>
<th>N strategy</th>
<th>No forecast</th>
<th>POAMA forecast</th>
<th>Correct forecast</th>
<th>Forecast efficacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk averse</td>
<td>$235,000</td>
<td>$402,500</td>
<td>$490,000</td>
<td>66%</td>
</tr>
<tr>
<td>Maximise GM</td>
<td>$410,000</td>
<td>$420,000</td>
<td>$527,500</td>
<td>9%</td>
</tr>
</tbody>
</table>

Finally we examine the ability of a POAMA forecast to hedge against the possible decrease in the number of good years that might be one consequence of global warming. Without a forecast, and using the conservative N strategy, a farmer makes 80% of his/her profits in 40% of the years at Nyabing on clay soil. Using a POAMA forecast, the same income is achieved in just 15% of years (see Figure E6).

Figure E6. Farm income as a percentage of the long-term (no forecast) income shown as a function of the number of years, sorted best to worst. Results are shown both without a forecast and using a POAMA forecast.

The findings in this Appendix have been reported at three conferences (McIntosh et al. 2010a, b; McIntosh et al. 2011).
Appendix F. Value of POAMA for mixed farming

Seasonal rainfall forecasts from the coupled ocean-atmosphere global circulation model POAMA have shown significant skill in forecasting rainfall season types in southern regions of the Western Australian wheat-belt. This seasonal forecast was used for management decision in mixed wheat-sheep farming systems. In forecasted wet rainfall seasons, N fertiliser applications in cropping were increased to the higher grain yield potential, sheep stocking rates were increased to take advantage of the higher pasture growth rates and unused pasture land became additionally available for cropping. In forecasted dry rainfall season-type years, N fertiliser applications in cropping were reduced to minimise inputs, however, the traditionally practiced low sheep stocking rate remained unchanged. The application of the POAMA seasonal rainfall forecast yielded between A$100,000 and A$200,000 extra income per average farm and year (A$66 ha⁻¹), well above any previous single-commodity forecast applications and has therefore widespread potential to improve decision making on mixed crop-livestock farms (Figure F1).

The results of this work have been reported in a manuscript attached to this report (Asseng et al. 2011c).

Appendix G. Value of short-term rainfall forecasts

Grain yields vary widely between seasons in rain-fed agriculture. The yield variability is strongly influenced by rainfall variability and a number of related crop management decisions. This report demonstrates how using seasonal rainfall forecasts to alter N application and the wheat/sheep mix can be of considerable value. However, a quantifiable value of short-term, 10-day rainfall forecasts for management decisions in cropping has not been determined yet. Here we report on the potential benefits of a hypothetical, always correct (100% skill) 10-day rainfall forecast which has been applied.
to trigger early and late in-season crop management decisions. If there is value from such a perfect forecast, then a case can be made for assessing the value of model forecasts.

A 10-day ‘correct’ weather forecast was assumed to predict rainfall in excess of 10mm at different stages during the season. Applying a 10-day rainfall forecast to commence sowing before the traditional start of sowing with the beginning of rainfall in autumn (dry sowing) can yield an extra 20,000 - 200,000A$/farm (i.e. 10 - 100A$/ha, for a 2000 ha cropping program) (Figure G1). Using such a short-term forecast to trigger late in-season decisions on late N fertiliser (Figure G2) and late fungicide applications (Figure G3) to control rusts (stem rust, *Puccinia graminis* and stripe rust, *Puccinia striiformis*) at the end-of-ear growth stage can increase yields and reduce fungi damage in late wet seasons with extra benefits of 10-160A$/ha. When 10-day rainfall forecasts are applied together within a season the extra benefits from correct short-term forecasts can be cumulative.

Fine-tuning the forecast length, rainfall triggers and exploring other possible crop decisions could yield further increased returns in cropping from short-term rainfall forecasts. Ultimately, using observed hindcasts of short-term rainfall forecasts to measure the forecast skill and the implication of occasional non-correct-skill forecasts will determine the actual value of such forecasts.

The results of this work have been reported in a manuscript attached to this report (Asseng et al. 2011c).

Figure G1. Simulated average (1980-2006) benefits from a correct 10-day rainfall forecast (>10mm in 3 days) for a 2000-ha cropping enterprise (or cropping component in a mixed farming enterprise) for dry-sowing decision making (A$/farm) for the average of four common soil types (duplex, clay, loamy sand, acid loamy sand) at Katanning and Nyabing, Merredin and Mullewa for initial dry conditions (open symbol) and initial wet conditions (30 mm PAW). The traditional crop sowing starts with the first significant rainfall (>10 mm within 3 days over the last 10 days and soil layer 5-10 cm at 50% soil water holding capacity). Following a 10-day forecast, sowing starts 10 days before the traditional day. Maximum sowing capacity of 200 ha/day was assumed. Wheat price at A$200/t, N fertiliser cost at A$1/kg N and a profit target of A$2 per each 1A$ invested in N fertiliser. Horizontal error bars represent standard deviation for rainfall variability, vertical error bars represent standard deviation for gross margins benefits caused by soil types. Linear regression for average values: $y = 0.70x -149; r^2 = 0.89$. 
Figure G2. Additional grain yield from 20 kg N/ha applied at end-of-ear growth stage during seasons with >10 mm rainfall within 3 days during 10 days after end-of-ear growth stage for Katanning (open bars), Nyabing (diagonal lines in bars), Merredin (crossed lines in bars) and Mullewa (filled bars) in the Western Australian wheat-belt. Wheat price at A$200/t, N fertiliser cost at A$1/kg N and a profit target of A$2 per each 1A$ invested in initial N fertiliser. Horizontal lines show additional yield required for break-even for the 20kg N/ha applied at a wheat price of 200A$/t (solid line) and 300A$/t (dashed line).

Figure G3. Additional grain yield from a A$25/ha-fungicide treatment applied at end-of-ear growth stage during seasons with >10 mm rainfall within 3 days during 10 days after end-of-ear growth stage for Katanning (open bars), Nyabing (diagonal lines in bars), Merredin (crossed lines in bars) and Mullewa (filled bars) in the Western Australian wheat-belt. Wheat price at A$200/t, N fertiliser cost at A$1/kg N and a profit target of A$2 per each A$1 invested in initial N fertiliser.
Appendix H. Frost damage

Frost damage and crop simulation modelling

Risk of yield loss in wheat due to spring frosts around the flowering stage is a constraint to wheat yield in some parts of the wheat-belt of Western Australia (WA). The occurrence of frost events is highest in late winter and declines into spring. In frost prone areas, late sowing of wheat to delay flowering into late spring to avoid the frost has been a traditional approach to minimise frost damage. However, wheat yields also decline with a delay in sowing date and flowering time due to the declining rainfall and increasing high temperatures during late spring. There is a trade-off between flowering early to get optimum rainfall and mild temperatures during grain fill but with a higher risk of frost, and flowering later to reduce frost risk but with the less optimum water supply and increasing risk of high temperatures during grain fill. Due to the nature of frost events, it is difficult to obtain non-frosted and frosted yields under the same experimental conditions, that is, all the factors are the same except for the incidence of frost. Consequently there is a lack of published data on the effect of frost on yield.

One strategy used by growers is to delay sowing in frost prone areas. But the cost associated with reduced yield potential with delayed sowing can be greater that the actual cost of frost losses over time. The current farmers practice is to minimize frost damage by managing time of sowing and cultivars to maximize average yield in the long term. For example, in Wandering the frost risk would be too high for any combination of sowing date and cultivar and therefore the farmers are choosing more frost tolerant crops than wheat, e.g. barley and oats. In Narrogin, where the frost risk is moderate, the current strategy is to avoid early sowings and to sow wheat only after mid May. In Cunderdin, where the frost risk is low but the yield decline with sowing date is large, the current strategy is to sow as early as possible, despite a low frost risk.

In this study we tried to determine the potential yield gain from having a frost forecast enabling growers to: a) delay sowing (or change cultivars) in seasons with a higher than average frost risk, and b) sow earlier in years with a lower than average frost risk.

Crop simulation model

We used the validated APSIM-Wheat model (v. 6) and historical weather data for the period 1957-2008 to define potential yields and potential frost damage for three locations in the Western Australian wheat-belt (Wandering, Narrogin and Cunderdin). Long-term simulations were run for seven sowing dates (sowing at 15 days intervals from the 10th of April to the 9th of July), three wheat cultivars (early, medium and late maturity types) and two soil types (clay duplex and deep sand). Crop management was simulated to reproduce current best practices in each location. The simulation experiments provided information on potential yields and yield damage from frost events with sowing date, and interactions with season, soil type and cultivar.

Frost and yield relationship

Using data from the frost events in 1998 in Western Australian (Knell 2001) and unpublished data (Biddulph, pers. comm.) we developed a semi-empirical relationship between minimum temperature around flowering and grain filling and yield losses due to frost in wheat. Additional data were from GRDC project DAW00162. Based on these data we estimated that screen temperatures below 2, 1 or 0 °C, during flowering would cause 20, 30 or 40 % yield reduction due to frost, and that temperatures below 0 °C during grain filling would cause a further 20 % yield reduction. Note that this reflects observed average yield damage from frost and might underestimate damage observed from more severe frost events. Note also that screen temperature is taken at 1.2 m height and is usually higher than the temperature at head height. Using this model of relative frost damage, we converted the simulated potential wheat yields into frost-affected yields or yields with yield penalties due to low temperatures during flowering and grain filling. The yield reductions due to frost obtained using this model have been compared to farmers common perception of frost penalties, and they compared well. However, as we concentrated on “average frost damage” at this stage, caution is required regarding the current conclusions.
Frost forecast

To define the frost forecast, we counted the number of days with temperature below 2 °C in September in the last 50-year period and divided the long term record into low or high frost risk years. The current management for frost is to reduce frost damage by managing time of sowing and cultivars to control flowering dates to maximize average long-term yields. That is, based on the break of the season (i.e. first significant rainfall in autumn) at a given year, the growers will first decide whether to sow or to delay sowing and then will chose the cultivar class (early, medium or late) that would maximises the long term average yield. For example, given a break of the season around the 10 May (DOY 130) farmers in moderate frost risk locations, such as Narrogin, will sow a late flowering cultivar. If the break occurs around the end of May (DOY 145) they would change to a medium or early flowering cultivar.

If a frost forecast could predict the occurrence of spring frost when growers are making seeding decisions in the previous autumn, this may allow growers to strategically change the sowing date and cultivar choice accordingly. To quantify the potential value of a frost forecast, the long-term average yields from not using a frost forecast were compared with the long-term average yield using a frost forecast.

Results

The simulations showed a steep decline of wheat yields to delays in sowing (Figure H1). The results indicated that late flowering cultivars would be preferred for early sowings in all locations and soil types. For sowing opportunities after the end of May, there were no marked differences between cultivars. The simulations also showed a steep decline of yield damage from frost with delays in sowing (Figure H2). Frost risk was defined as the chance of having at least one day with minimum temperature below 2°C during the flowering period. The frost-yield model gave yield reductions of 20 to 60 %, which were consistent with farmers and consultants experience in the different locations. We combined the frost damage model with the APSIM simulated potential yields to obtain frost-affected yields, shown as average yields for the 50 years period in Figure H3 (dotted lines).

![Figure H1](image.png)

Figure H1. Long term average simulated yields versus sowing date for a) Narrogin and b) Cunderdin for an early (■), medium (○) and late (▲) flowering cultivar on a heavy soil.
The proposed management is to adjust the sowing date for the particular season using the forecast of low or high frost risk year (we did this retrospectively, so it assumes a perfect forecast). We sowed the crop according to current practices in the low frost risk years or delayed the sowing by 15 days in the high frost risk years of the 50 year simulation study. Table H1 shows the flowering dates and average yields for the 50 year period using current management or using the frost forecast at the beginning of the season.

Given the yield sensitivity to frost used in our model and assuming a frost forecast of low or high risk in September only, there seems to be no benefit in using a frost forecast to adjust crop management (Table H1). This might be different when considering more severe frost damage instead of the average damage. As an alternative to frost forecast in managing frost, a hypothetical wheat cultivar with one degree more tolerance to low temperatures was simulated. Such a new cultivar would significantly improve yields (Table H1).

The initial approach tested in this model may be useful in further defining the sensitivity of the interaction between potential frost damage and the actual yield loss associated with delayed sowing to minimise frost risk. It will be further developed to try and answer questions about what level of frost damage does the yield penalty outweigh the benefit from frost risk? How accurate does a frost prediction need to be to enable cost effective management decisions? For example, do we just need to predict the years when we get severe damage, and avoid growing frost susceptible crops in those
years? What is the effect of reducing frost susceptibility of the crop through agronomic and genetic improvements? Will a 0.2º 0.5º, 1.0ºC improvement have a real effect?

Table H1. Current optimum sowing dates, corresponding flowering dates and simulated grain yields (t/ha) for three locations and two wheat cultivars (Late=Late flowering cultivar; Medium = Medium flowering cultivar). Delayed sowing date due to frost forecast, corresponding flowering dates and simulated grain yields.

<table>
<thead>
<tr>
<th></th>
<th>Wandering (High Rainfall)</th>
<th>Narrogin (Medium-High Rainfall)</th>
<th>Cunderdin (Medium Rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current optimum sowing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>date</td>
<td>10 May</td>
<td>25 May</td>
<td>10 May</td>
</tr>
<tr>
<td>Average flowering date</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for current sowing</td>
<td>27 Sep</td>
<td>26 Sep</td>
<td>11 Sep</td>
</tr>
<tr>
<td>Average yield with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>frost damage</td>
<td>3.2</td>
<td>2.9</td>
<td>3.3</td>
</tr>
<tr>
<td>Delayed sowing date</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>due to frost forecast</td>
<td>25 May</td>
<td>9 Jun</td>
<td>25 May</td>
</tr>
<tr>
<td>Average flowering date</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for delayed sowing</td>
<td>10 Oct</td>
<td>8 Oct</td>
<td>26 Sep</td>
</tr>
<tr>
<td>Average yield using a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>frost forecast</td>
<td>3.1</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Average yield with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>frost tolerant (1 °C)</td>
<td>3.6</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>cultivar</td>
<td></td>
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</tr>
</tbody>
</table>

**Climatology and frost occurrence**

We started with an investigation of the climatology of low temperature events as background to the wider investigation of predictability of frosts events. The initial premise was that model forecasts would be done as seasonal (i.e. 1 to 3 months duration) mean temperature anomalies at varying lead times. For example, a typical forecast might be for the spring (SON) minimum temperature anomaly to be 1.5 degrees below average. We wished to determine whether this level of forecast carried any information about the relative frost risk, that is would such an anomaly translate into a significant change in frost risk at a location.

The study was to define how frost risk was related to seasonal mean temperatures. We focused on historical climate records from high quality Bureau of Meteorology stations at Cunderdin, Wandering and Lake Grace. We examined the climate during the growing season (1 May (DOY 121) to 31 October (DOY 304)) with particular emphasis on inter-annual variability and temperature extremes during spring. A detailed climatology of occurrence and timing was developed for each site. As well, we investigated impacts of seasonal temperatures on thermal indicators of plant development.

Example: Incidence of cold events with thresholds 0, 1, 2°C, from 1 September- 30 November for Lake Grace (1957-2008) vs. mean minimum temperature (1 September-30 November) (Figure H4).

We found that there was a relationship between seasonal temperature anomalies and frost risk - as might be expected. However, the relationship was different between positive and negative seasonal anomalies. A season with a strongly positive $T_{min}$ anomaly had a low risk of frost events, but a strongly negative anomaly did not necessarily meant a high frost risk. There were some years that were notably cold, yet did not have a high incidence of low temperature events. Also, there was little shift in risk for anomalies close to the mean. This means that a forecast is only likely to represent a shift in risk if there is a large temperature anomaly predicted. It also suggests that the model must be able to reproduce the know range of anomalies.
The relationship was strongest for events of less than 2 degrees C, but was weak for more intense events (i.e. less than 1 or 0 degrees). Therefore there may be value in predicting the risk of mild frost events, but maybe not for severe frosts. The relationship was poorer for a warmer site such as Cunderdin. This has implications for the regional application of the frost forecast (also relevant to the study of the trade-off between sowing date and frost risk).

![Incidence of low temperature events Lake Grace (1957-2008), 1 September- 30 November](image)

Figure H4. Incidence of cold events with thresholds 0, 1, 2°C, from 1 September- 30 November for Lake Grace (1957-2008) vs. mean minimum temperature (1 September-30 November).

An alternative approach to using predicted seasonal temperature anomalies is to obtain counts of number of days that $T_{\text{min}}$ falls below a set threshold (can be set for the model’s climatology). The key obstacle in POAMA is how to do that at the grid scale the model operates at. This leads on to a need for spatial downscaling of the forecast. We could also extend the study to high temperature risks.

**References**


**Appendix I. Value of POAMA for determining cultivar**

A seasonal climate forecast of rainfall or temperature might be of value in determining the wheat cultivar to be planted. Different cultivars have different maturing times, in other words, they require a different number of degree days to reach maturity. If a forecast made at planting time is to be valuable, then it should be possible to see a distinct difference in yield between cultivars in warm and cold years and also possibly in wet and dry years.

Figure I1 shows modelled yield for different N applications in these four climate categories at Katanning on a clay soil with a dry initial soil water profile. Although yield generally increases with increasing N, when the cost of N is taken into account, the equivalent gross margin plots decrease beyond about 80 kg/ha of N. It is clear from Figure I1 that below 100 kg N/ha, there is no change in the preferred cultivar in the different climate categories. On the basis of these results, a farmer would always choose to plant the medium maturing variety Wyalkatchem regardless of the forecast.

Similar results are obtained for different soil types; acid, duplex, loam and sand. Although the preferred cultivar changes with soil type, there is no dependency on temperature or rainfall. Furthermore, these results apply at different locations: Nyabing, Merredin and Mullewa.
We conclude that there is no basis for using a seasonal climate forecast of temperature or rainfall for determining cultivar at a range of locations in the south-west Western Australian wheat belt on any of the typical soil types.

Figure II. Yield (tonnes/ha) as a function of N application (kg/ha) for Katanning on a clay soil with dry initial soil water profile for 4 climate categories: above and below median maximum temperature, and above and below median rainfall. Climate data for the years 1900-2009 are used. The different coloured curves are for three different cultivars: Kulin (short maturing, red), Wyalkatchem (medium maturing, black) and Spear (long maturing, blue).

Appendix J. Future directions

Several projects/project components are suggested as a continuation of the current project:

- To improve our understanding of the rain bringing systems in WA as the basis for improving POAMA and consequently seasonal forecasts from POAMA, the development of an automatic frontal system recognition scheme to complement the cutoff low scheme is suggested. This would also be beneficial for other parts of Australia.
- The current project has identified that the method POAMA uses to generate the ensemble members is not ideal, and this is an area which requires substantial further work to explore better ways to generate ensemble forecasts for decision making in agriculture.
- Diagnose the relationship between moisture pathways in SWWA and long-term trends in synoptic systems and rainfall.
- Identify dynamical controls on blocking and cutoff lows in observations and use this information to improve POAMA’s simulation of these features.
- Heat stress during grain filling can severely reduce yields in many wheat growing regions of the world, including WA. It is suggested to explore POAMA’s heat stress forecasts and potential value for decision making in cropping based on the framework developed for frost forecast in this project (heat event forecasts are likely to have higher skill than frost forecasts). It should be examined whether sowing crops earlier, or using early maturing cultivars (as long as break of the season allows that), or switching crops to less heat sensitive species is beneficial in years of forecasted high frequency of heat events. It could also be explored
whether to adjust late inputs (late N and fungicides) according to heat stress forecasts, increase inputs with low heat stress forecasts, or reduce inputs with high heat stress forecasts during the season.

- The current analysis has shown that the value of a forecast can change with initial soil water conditions. Therefore, a forecast should be linked to other systems knowledge to enhance the value of the forecasts. The relatively short hindcasts limits the analysis to two category forecasts and does not allow splitting the categories into other categories of systems knowledge (e.g. early or late sowing opportunity; low or high initial soil water conditions) or considering more extreme season types (e.g. terciles). Therefore it is proposed to use longer term hindcasts developed in the current project to enable multi-scale forecasts which would allow better management of the wide range of rainfall distribution instead of being limited to only two categories with each covering a wide range of rainfall seasons. This would also allow to link forecasts with other systems knowledge (e.g. soil water content, start of season) which is currently not possible due to the limited hindcast length.

- Transition POAMA to the ACCESS system: Rainfall forecast skill is generally comparable among the three POAMA-2 configurations, suggesting other biases other than mean SST bias are limiting Australian rainfall skill. One possible candidate is rainfall mean biases, particularly too little rainfall seen in tropical Indian Ocean in all three configurations. This suggests that further skill improvement over SWWA requires reducing tropical mean rainfall biases in regions such as tropical eastern Indian Ocean where SST forcing through convection processes excite teleconnection influences on rainfall over SWWA. This knowledge will be used in developing the future ACCESS based POAMA system.

- From a model/forecast improvement perspective, priorities for the extension of the project into years 4 and 5 are related to evaluation of the atmospheric component of the next version of POAMA. This is where we believe improvements need to be made to improve the model tropical simulation and its teleconnection to SWWA climate. POAMA-3 will use the ACCESS based atmospheric model and priority should be given to evaluating how this model simulates the tropical and regional rainfall variability compared with POAMA-2. In particular, progress can rapidly be made in investigating the impact of increasing resolution. This would help guide the best configuration for POAMA-3 that would give improved skill in SWWA.

- The current project indicated a potential value of short-term forecasts for dry sowing and in-season crop management decisions. Therefore it is proposed to test the value of multi-week POAMA and European Centre for Medium Range Weather Forecasting (ECMWF) 10-day short-term forecasts for sowing opportunity (note, current project looks at perfect 10-day forecasts only), in-season N and fungicide management with a sliding window linked to crop phenology. Potential links to WATL multi-week products should be explored.

- The high potential value of seasonal rainfall forecast for mixed crop-livestock farming systems suggested that there are further opportunities to use forecasts on whole farm systems. Including livestock expertise (e.g. Dean Thomas, CSIRO Livestock Industries) and dynamic livestock modelling capacities (similar to the dynamic crop modelling approach) could further enhance the application of POAMA forecasts in livestock-crop farming systems, including specific land allocation according forecasts considering soil type and initial conditions.
Appendix K. Project Proposal: Summary, Objectives, Outputs

From the original project proposal:

Project summary

Seasonal climate forecasts made by the Bureau of Meteorology/CSIRO’s coupled ocean/atmosphere model will be tested for skill and value in the context of wheat-based farming systems in southwest Western Australia. The forecasts will be benchmarked against existing forecast systems using several decades of hindcasts. A novel aspect will be the availability of ensemble forecasts which will provide an estimate of forecast reliability. A technique will be developed to reduce a major source of forecast error (coupled model bias) and a new set of hindcasts produced. The skill and value of these hindcasts will be assessed. Both northern and southern cropping regions in WA will be studied, and rainfall skill assessed during the growing season, as well as for early, mid and late periods during the season. The potential economic returns from both sets of forecasts will be evaluated within a SWWA wheat-based farming systems framework in combination with other systems knowledge.

Project objectives

1. Improve prediction of early, mid and late growing season rainfall in distinct climate regions in southwest Western Australia relevant to the wheat industry using a global circulation model.
2. Establish estimates of forecast uncertainty based on the range of model forecasts, the range of on-farm outcomes, and benchmarking against existing forecast schemes.
3. Improve predictability of soil moisture, yield and pasture growth through linking seasonal forecasts to farm practice, soil type and existing information such as stored soil moisture.
4. Improve articulation of cereal farm practice options, with potential spin-offs to the grazing industry, based on forecast skill and reliability.
5. Establish foundations for ongoing strategic investment in improvement of global circulation models.

Outputs

- Assessment of skill and value of POAMA-1.5 hindcasts for SWWA, including “seasonal outlook” style forecasts;
- Benchmark of this skill and value against existing forecast systems;
- Evaluation of best way to use ensemble forecast information, including estimating forecast uncertainty and the effect on management practices;
- Assessment of incremental skill from new versions of POAMA, including the value with bias correction scheme developed in this project (in POAMA-2.5);
- Range of optimum management strategies based on coupled model forecasts combined with other systems information; and
- Evaluation of strengths and weaknesses of POAMA/ACCESS simulation, with suggestions for improvements.

Outcomes

- Increased skill, value and reliability of seasonal climate forecasts for wheat growers and graziers in SWWA;
- Foundation established for ongoing strategic investment in Australia’s seasonal climate forecast model;
- Roadmap for climate model improvement; and
- Better management strategies based on climate forecasts.