South Eastern Australian
Climate initiative

Project 1.3.1

Climate change influence on changes in evapotranspiration, runoff and drainage across south-eastern Australia through both physical and ecological processes

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State Government Victoria Department of Sustainability and Environment

National Research FLAGSHIPS Water for a Healthy Country

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Abstract

The Australian Water Availability Project (AWAP) was developed to monitor the terrestrial water balance of Australia. Measurements and model predictions were combined using model-data fusion methods. Funded jointly by CSIRO Marine and Atmospheric Research (CMAR), the Bureau of Meteorology (BoM) and the Bureau of Rural Science (BRS), AWAP establishes soil moisture and all water fluxes that contribute to soil moisture from 1900 to the present on a 5km grid across the Australian continent. The water fluxes that contribute to soil moisture include rainfall, transpiration, soil evaporation, surface runoff and deep drainage (Raupach et al., 2007).

The aims of this project are to evaluate subsequent effect of the rainfall decline on other surface water balance variables, to investigate how the dominant large-scale modes of variability affecting rainfall affects in turn the regional water balance with a particular focus on

1. the role of the predominantly autumn rainfall decline and

2. the amplification of the rainfall decline into a very large river inflow decline.

This has been done by investigating the following AWAP variables: upper and lower soil moistures, total evaporation and total runoffs and comparing these with the most important atmospheric forcing: rainfall.

The analysis confirms that deep soil moisture and total runoff in winter and spring are strongly affected by the intensity of the sub-tropical ridge (STR-I) one season ahead. This reflects the strong influence of the STR-I on the rainfall one season ahead. During the last decade, the STR intensification has been larger in JJA than in SON (Timbal and Fernandez, 2009) and could partly explain the much larger reduction in river inflows in spring compared to the rainfall reduction in spring (Timbal, 2009).

Significant research highlights, breakthroughs and snapshots

This project has highlighted the potential to better understand beside the rainfall decline, how the on-going climate change is affecting the entire water balance across south-eastern Australia (SEA) and therefore to provide a more pertinent understanding for water managers. These early results are very encouraging. Further analysis and development using AWAP products are planned as part of the Phase 2 of SEACI; it is expected to help advance our understanding of the water balance across the SEACI area of interest.

Objective: Analyse the relationship between a range of indicators of large-scale mode of variability and several hydrological variables across south-eastern Australia.

Using the AWAP variables, it was possible to show that:

- There is a strong consistency on the influence of the STR-I on all related moisture variables, rainfall and subsequently on both soil moistures, total evaporation and runoff;

- There is no lag effect between rainfall and upper soil moisture, as well as total evaporation; on the contrary, both lower soil moisture and runoffs show lower correlations in the early part of the wet season that peaks in the latter part of the wet season (July to November);

- The spatial extension of the area of significant correlation between STR-I and deep soil moisture and runoffs is much reduced compared to rainfall but covers most of the important catchment areas in SEA;

- A part of the larger reduction in river inflow compares to the rainfall signal is explained by lag correlation between the STR-I and deep soil moisture and runoff in winter and spring;

- Contrary to other large-scale influences (ENSO and IOD), the STR intensification appears as the only one which exhibits increased lag correlations compared to simultaneous one.

Further details are included in the attachment.

Summary of links to other projects

This project, part of the extension of Phase 1 of SEACI, builds on earlier and on-going projects:

1. The detection of climate change across south-eastern Australia (project 1.1.1, Timbal and Murphy, 2007a);

2. The role of large-scale climatic modes of variability in the rainfall decline and in particular the dominant influence of the strengthening of the sub-tropical ridge (STR) (project 1.1.2, Timbal et al., 2007);

3. The investigation of the relationship between the STR build up to global warming and its attribution to anthropogenic forcings (project 1.1.1P, Timbal and Smith, 2009); and

4. A re-evaluation of the spatial and seasonal characteristics of the rainfall decline across south-eastern Australia (project 1.2.1P, Timbal and Fernandez, 2009).

Publications arising from this project

Raupach M, P. Briggs, V. Haverd, E. King, M. Paget, C. Trudinger, K. Whan, D. Jones, N. Plummer, D. Barratt and J. Sims, 2010: Dynamics of the Australian Water Balance from 1900 to 2008 *(in preparation).*

Acknowledgement

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References

Raupach M., P. Briggs, E. King, M. Paget and C. Trudinger, 2007: Australian Water Availability Project (AWAP), CSIRO Marine and Atmospheric Research Component: Final Report for Phase 3", CSIRO Marine and Atmospheric Research, Canberra, Australia.

Attachment

Climate change influence on changes in evapotranspiration, runoff and drainage across SEA, through both physical and ecological processes

Prepared by
Bertrand Timbal, Kirien Whan and Michael Raupach

Introduction

The Australian Water Availability dataset

The Australian Water Availability Project (AWAP) was developed to monitor the terrestrial water balance of Australia. Measurements and model predictions were combined using model-data fusion methods. Funded jointly by CSIRO Marine and Atmospheric Research (CMAR), the Bureau of Meteorology (BoM) and the Bureau of Rural Science (BRS), AWAP establishes soil moisture and all water fluxes that contribute to soil moisture from 1900 to the present on a 5km grid across the Australian continent. The water fluxes that contribute to soil moisture include rainfall, transpiration, soil evaporation, surface runoff and deep drainage (Raupach et al., 2007).

Gridded meteorological data, such as precipitation, temperature and solar influx, forces the model. Both upper- and lower-layer soil moisture are model outputs. Upper layer soil moisture is defined as the upper 20 centimetres, while the lower layer is from 0.2 – 1.5 metres. Levels of soil moisture are determined by variables such as transpiration, soil evaporation, surface runoff and leaching.

Transpiration is defined as the lesser of energy-limited and water-limited transpiration rates. The energy-limited transpiration rate is defined by the Priestley-Taylor rate attenuated by the vegetation cover fraction. The water-limited transpiration rate in each soil later is specified using a rate parameter which controls the decay of water extraction by roots from a drying soil under water-limited transpiration and full vegetation cover. Soil evaporation is the product of an upper-limit value (Priestley-Taylor evaporation), the relative water content in the upper soil layer and the fraction of bare soil. These two parameters combine to total evapotranspiration (FWE).

Surface runoff is given by a step function, all precipitation runs off when the upper-layer soil is saturated and there is no runoff otherwise. Leaching or drainage downward out of each soil layer is given by the product of saturated hydraulic conductivity and a power of the relative water content in each layer. Surface runoff and leaching combine into total runoff, or local discharge of water from the soil column (FWDis).

In this report, all four variables: upper and lower soil moistures, total evaporation and total runoffs are investigated and compare with the most important atmospheric forcing – rainfall.

The influence of the sub-tropical ridge on water balance

As part of the analysis of the observed changes in the climate of south-eastern Australia (SEA) during Phase 1 of SEACI, it was found that predominantly (more than 60 per cent) the rainfall decline occurred in autumn, it was large but not unprecedented and was record-breaking for water availability (e.g. river inflow) across SEA (Murphy and Timbal, 2008). Subsequently, an analysis of the large-scale modes of variability known to influence the Australian climate (e.g. El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) or the Southern Annular Mode (SAM)) showed that they were unlikely to have contributed significantly to the rainfall decline across SEA due to its strong autumn signature (Timbal and Murphy, 2007b). On the contrary it was found that the Mean Sea Level Pressure (MSLP) increase during the late 20th Century which has been observed above southern Australia (Timbal and Hope, 2008), a manifestation of the sub-tropical ridge (STR) intensification could explain up to 70 per cent of the rainfall decline across SEA (Timbal et al., 2007).

Recently, the rainfall decline across SEA has worsened to become largest long-term rainfall deficit in the instrumental record (Timbal, 2009). Its signature is predominant across the South-Western part of Eastern Australia (SWEA) a critical area for runoff and river inflow across SEA (Timbal and Fernandez, 2009).

The Drosdowsky (2005) sub-tropical ridge intensity (STR-I) index was used and its impact of moisture variables available from the AWAP was evaluated. Correlations between monthly means of AWAP variables and STR-I were computed and averaged over three months from 1900 to 2007 and shown for rainfall (Fig. 1), surface and deep soil moisture (Figs. 2 and 3), total evaporation (Fig. 4) and total runoff (Fig. 5), key elements emerging are:

- There is a very strong consistency on the influence of the STR-I on all related moisture variables, negative correlations at certain time of the year are apparent across SEA on rainfall and subsequently on both soil moistures, evaporation and runoff;
- There is no lag effect between rainfall and upper soil moisture, the negative correlation with the STR-I starts in autumn (MAM) is maximum in early winter (MJJ) and decreases toward late spring (OND); this is also the case for total evaporation;
- On the contrary, both lower soil moisture and runoff show lower correlation in the early part of the wet season compared to the other variables but not so in the latter part of the wet season (July to November);
- That difference creates a lag effect where the largest correlation between the STR-I and deep soil moisture is observed in spring (ASO) while for runoff it is fairly similar during the entire wet season; and
- The spatial extension of the area of significant correlation between STR-I and deep soil moisture and runoffs is reduced compared to rainfall, evaporation and upper soil moisture but covers most of SWEA and the Great Diving range (GDR) further East and North; this area covers the important catchment areas for most rivers in SEA (including the Murray river).

Beside the consistency of the impact of the STR on all important surface water balance variables available from the AWAP, the emergence of a lag effect on deep soil moisture and runoff is worth exploring further. This is particularly important in light of the very large inflow reduction in most rivers across SEA compare to the rainfall signal (Murphy and Timbal, 2008).

It was then hypothesised that while temperature increase could be a factor in explaining the largest inflow signal, the seasonal signature of the rainfall decline (predominantly in autumn) could also be a contributor. The role of the temperature increase was latter confirmed (Cai and Cowen, 2008). Using the AWAP, we have a tool to investigate the possible lag effect between rainfall decline predominantly in autumn and total runoff which is largest in winter and equally as large in spring; it peaks across SEA in JJA to ASO (Fig. 6).

Lag correlations between large-scale indicators and water balance

In this analysis, lag correlations between three climate indices and the two AWAP surface water balance variables that showed earlier a lag effect (lower soil moisture –Figures 6 and 7- and total runoff –Figures 8 and 9) are reported for winter and spring. Zero, three months and six month lag correlations were computed. A large number of climate indices were used, here we are focusing on three essential indices:

1. the Niño4 (160°E-150°W, 5°N-5°S) SST anomalies as the ENSO indices most relevant for SEA rainfall (N4);

2. the Saji et al. (1999), Indian Ocean Dipole Mode Index (DMI); and

3. the Drosdowsky (2005) STR-I index.

Although it was shown earlier that ENSO and IOD have not contributed to the rainfall decline due to its autumn signature, it is interesting to compare the lag effect of these three indices on AWAP variables which are showing a tendency to display a lag effect.

The main points to note on these calculations for winter (comparing simultaneous and three-month lag correlations) are:

- Three-month lag correlations between lower soil moisture are significant with both N4 and STR-I but in different parts of SEA: along the Eastern Sea Board (ESB) and Northern part of the Murray-Darling Basin (NMDB) for N4 and in SWEA for STR-I;
- The lag correlation are lower than simultaneous correlations for the STR-I but higher for N4;
- The DMI has no significant lag correlation anywhere across SEA which is consistent with a lack of relationship with rainfall in MAM and the fact that IOD event do not form until winter;
- All these findings on lower soil moisture are equally valid for total runoff.

In spring, it is worthwhile comparing, simultaneous, three-month and six-month lag correlations:

- The DMI has the largest simultaneous correlations in spring of the three indices used for soil moisture, consistent with the fact the IOD and its influence across Australia peaks in spring;
- Results are similar for total runoff although all three large-scale indices have lower correlations;
- As far as three-month lags correlations are concerned, the most significant relationship is with the STR-I, its signature across SEA is similar to the DMI signature but correlation are higher;

- That previous findings is due in part to the fact that he lag correlations between STR-I and deep soil moisture is larger than the simultaneous one (this is also the case for total runoff);
- Three-month correlations with N4 is reduced across SEA to the ESB while simultaneous ones were significant across large part of SEA including the GDR;
- Six-month lag correlations are in most instances insignificant across most of SEA with the exception of N4 along the ESB and STR-I in small pockets along the coast in SWEA.

That analysis confirms the earlier results that deep soil moisture and total runoff in winter and spring are strongly affected by the STR-I of the season ahead which is most likely due to the strong influence of the STR-I on the rainfall the season ahead. This is particularly true in spring when the impact of the STR-I on rainfall start to be reduced as it lead to a larger impact on SON total runoff than the simultaneous effect. Since during the last decade the STR intensification has been larger in JJA than in SON (Timbal and Fernandez, 2009), it is important and could explain a part of the larger reduction in river inflows compared to the rainfall reduction which is small in spring (Timbal, 2009).

If indeed, that delay mechanism for lower soil moisture and total runoff compare to rainfall is part of the explanation for the enhancement of the signal for river discharge, it enhances the importance of the STR intensification, since it is the only large-scale influence (other being considered here are ENSO and the IOD) which exhibits increased lag correlations compared to simultaneous one.

Conclusions and future perspective

This project has highlighted the potential to better understand beside the rainfall decline, how the on-going climate change is affecting the entire water balance across the SEA and therefore to provide a more pertinent understanding for water managers. These early results are very encouraging; it is expected that further analysis and development using AWAP products during Phase 2 of SEACI will help advance our understanding.

A particular focus will be to use advance statistics to better understand the influence of large-scale modes of variability and their interactions. Correlation, regression and principal components analysis as used here, have been the cornerstone of climatic research. Such methodologies, however, make assumptions about linearity that may not be always valid. Developments in nonlinear statistics have made exploration of nonlinear processes possible and in particular it is planned to use Classification and Regression Trees (CART), a relatively new and powerful regression-based technique that is capable of accounting for nonlinear effects and has many possibilities. Such analysis is particularly informative when there are multiple predictors and when the relationship between variables is nonlinear, as is it is most likely the case between remote climate teleconnections (e.g. ENSO or the IOD) and regional drivers influencing the local rain (e.g. the STR).

Statistical relationships between variables are the basis for the decision rules that are used to split the data into increasingly homogenous groups. CART has been used to successfully predict fire season severity from atmospheric circulation anomalies. Decision trees were grown that classified, and thus predicted, fire season severity based on MSLP in a key region between Tasmania and New Zealand, giving a valuable insight into the prediction of fire season severity in SEA (Bessell, 2006; Edwards, 2002).

There is considerable potential in the use of this methodology for examining the internal associations between large-scale modes of climate and the associations between the drivers and SEA climate variables. CART allows examination of multiple nonlinear interactions between drivers that effect climate and hydrology. Decision rules based on the state of the major large-scale drivers of climate will be developed to see how their phases are associated with climate and hydrology variables in SEA. Data is divided into increasingly homogenous groups based on decision rules about the state of the large-scale drivers of climate. This will give information about which interactions between large-scale drivers are important for particular climate and hydrological state and which combinations of large-scale drivers result in particular hydrological regimes.

A first step will be to investigate how the intensity and position of the STR act together and are associated with rainfall. It was shown using linear statistic to have mostly no additional effect (Timbal and Fernandez, 2009), this finding is somewhat surprising and worth investigating further using more advance statistical tools such as the CART methodology.

In a second step, the combined influence of the STR and the remote teleconnections will be studied. By classifying climate and hydrological data into groups on the basis of STR, SAM, ENSO and IOD data, the drivers with the largest influences can be identified as well as the relationships between the drivers. Decision rules about the state of SAM, ENSO and the IOD can be used to split the pressure data into homogenous groups. These rules can show which phases and combinations of the remote drivers are associated with specific states of the STR. The combined effect of the large-scale drivers on climate variables such as rainfall and temperature can then be determined and compared with the relationships between the large-scale drivers and hydrological variables, to ascertain if there is a stronger relationship between hydrological variables and large-scale modes of climate than with climate variables and the remote drivers.

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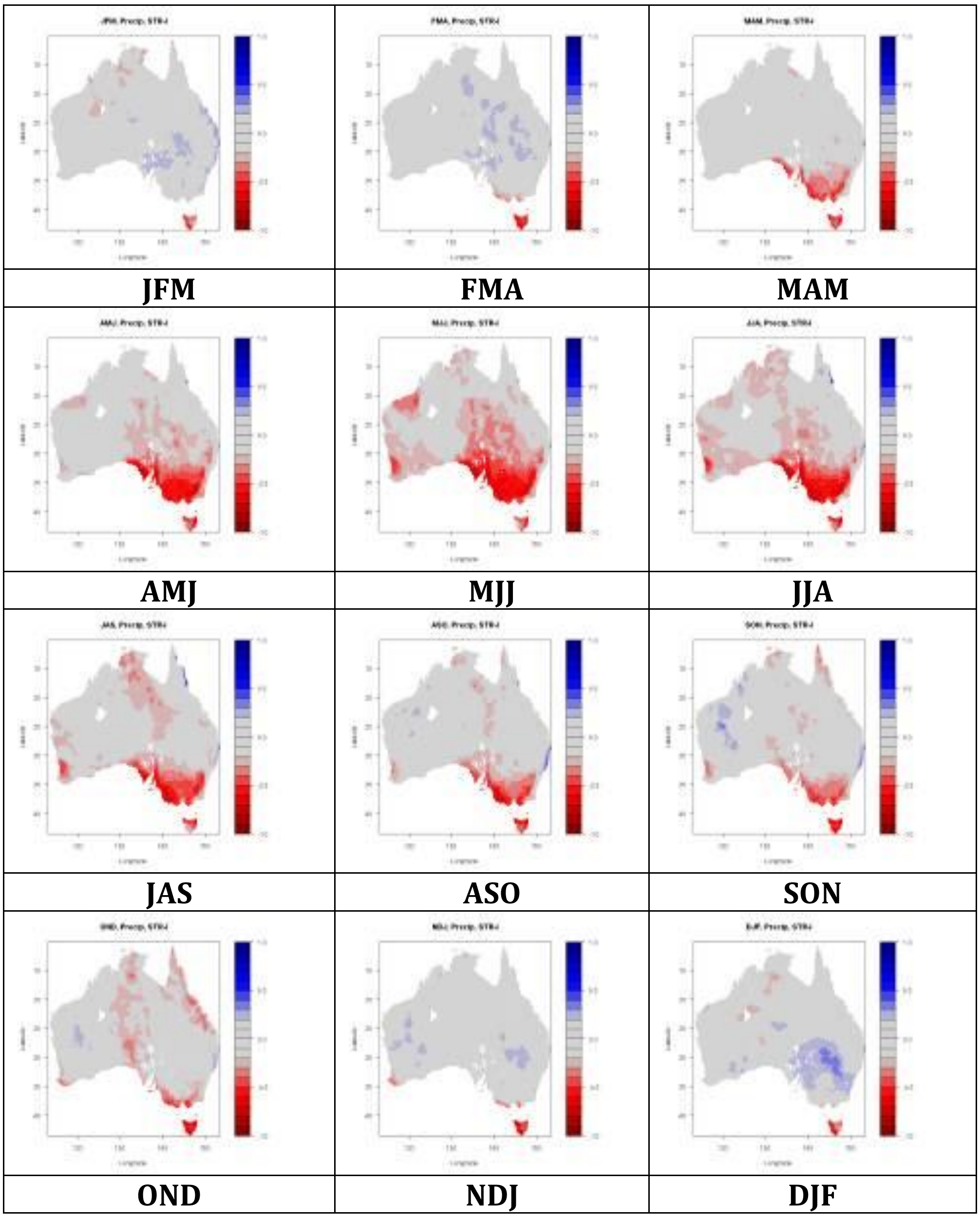
Tables and figures



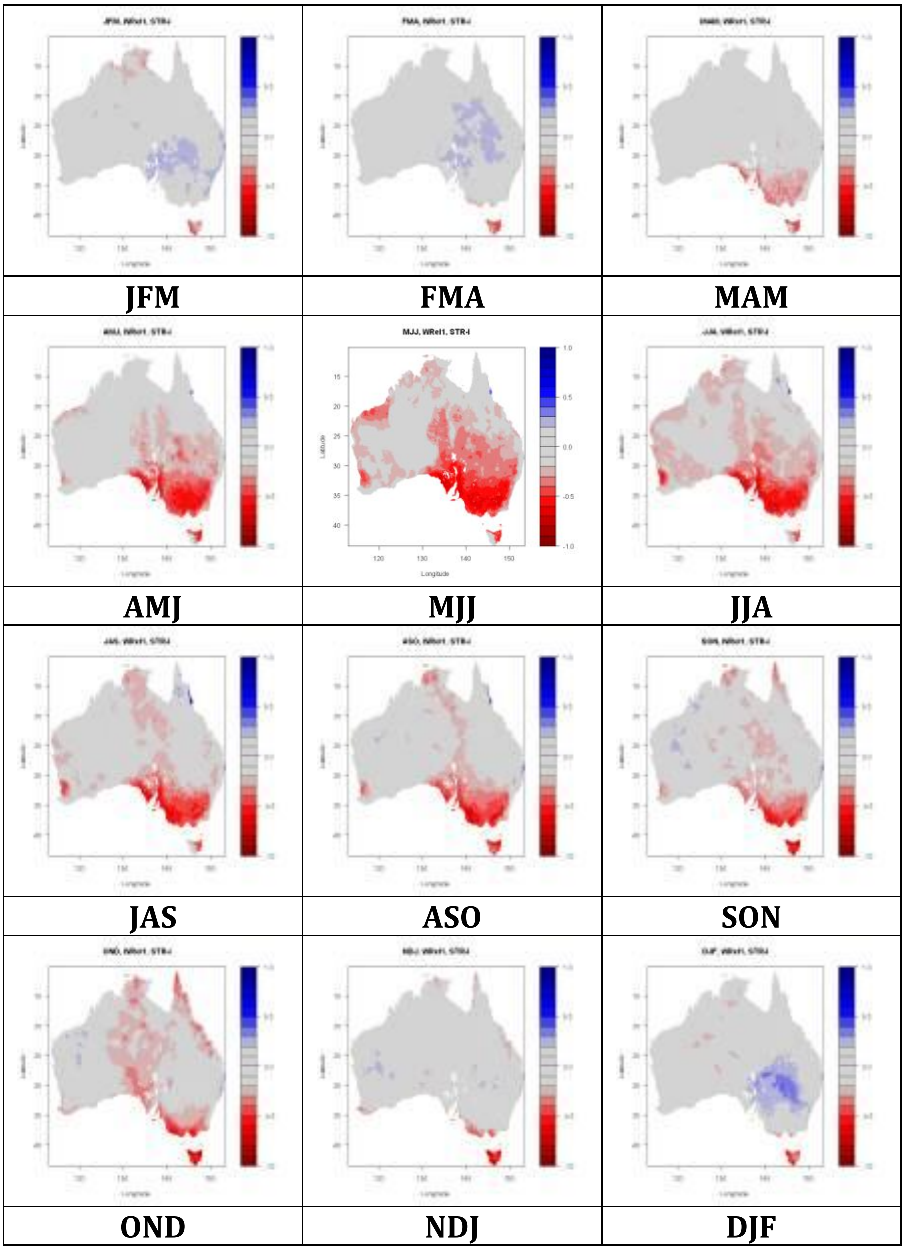
JFM FMA MAM

AMJ MJJ JJA

JAS ASO SON

OND NDJ DJF

Figure 1: *Month by month, three-month average correlations between the sub-tropical ridge intensity and rainfall across Australia, based on observations from 1900 to 2007; only correlation significant above the 95 per cent level are shown.*



JFM FMA MAM

AMJ MJJ JJA

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Figure 2: *As per Fig. 1 but for upper soil moisture (20cm deep)*

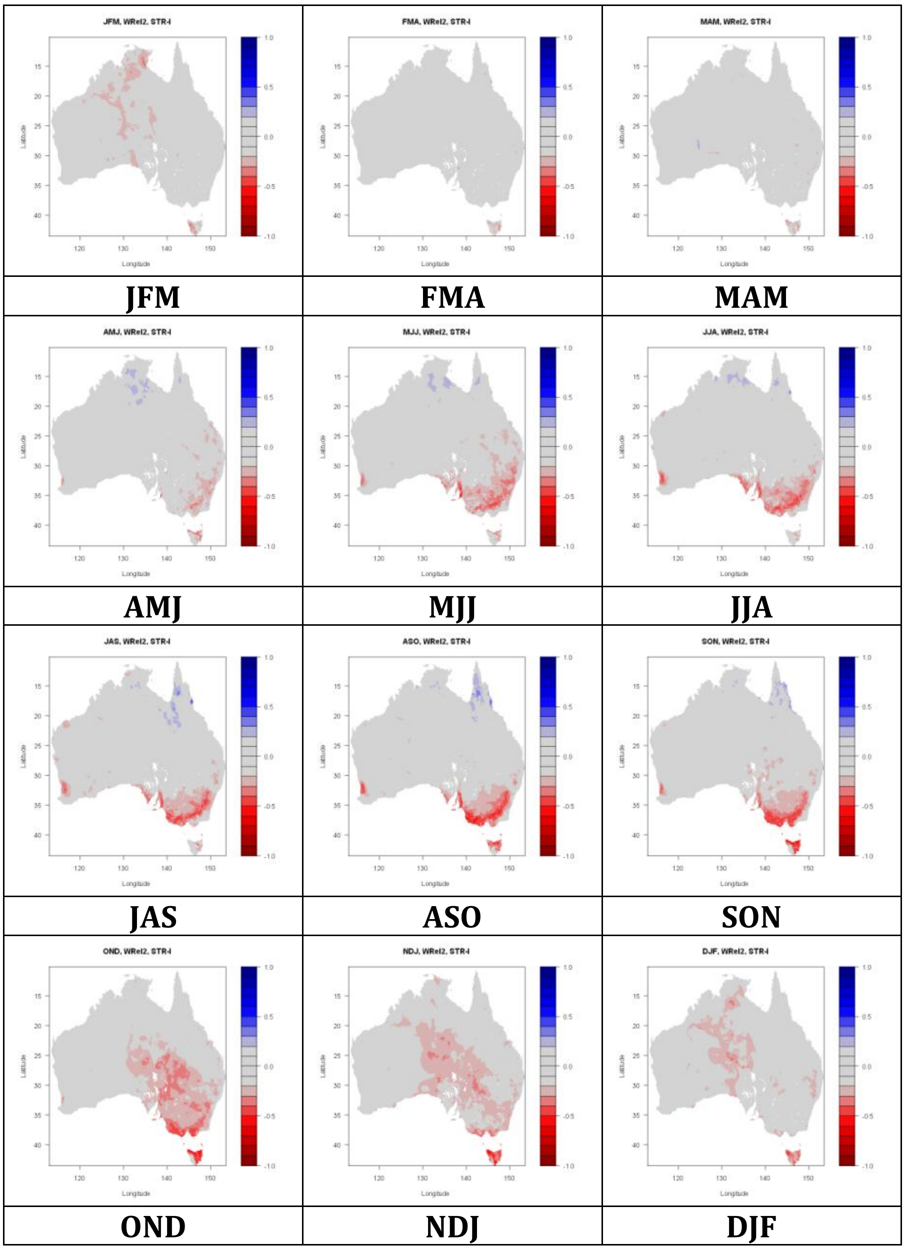

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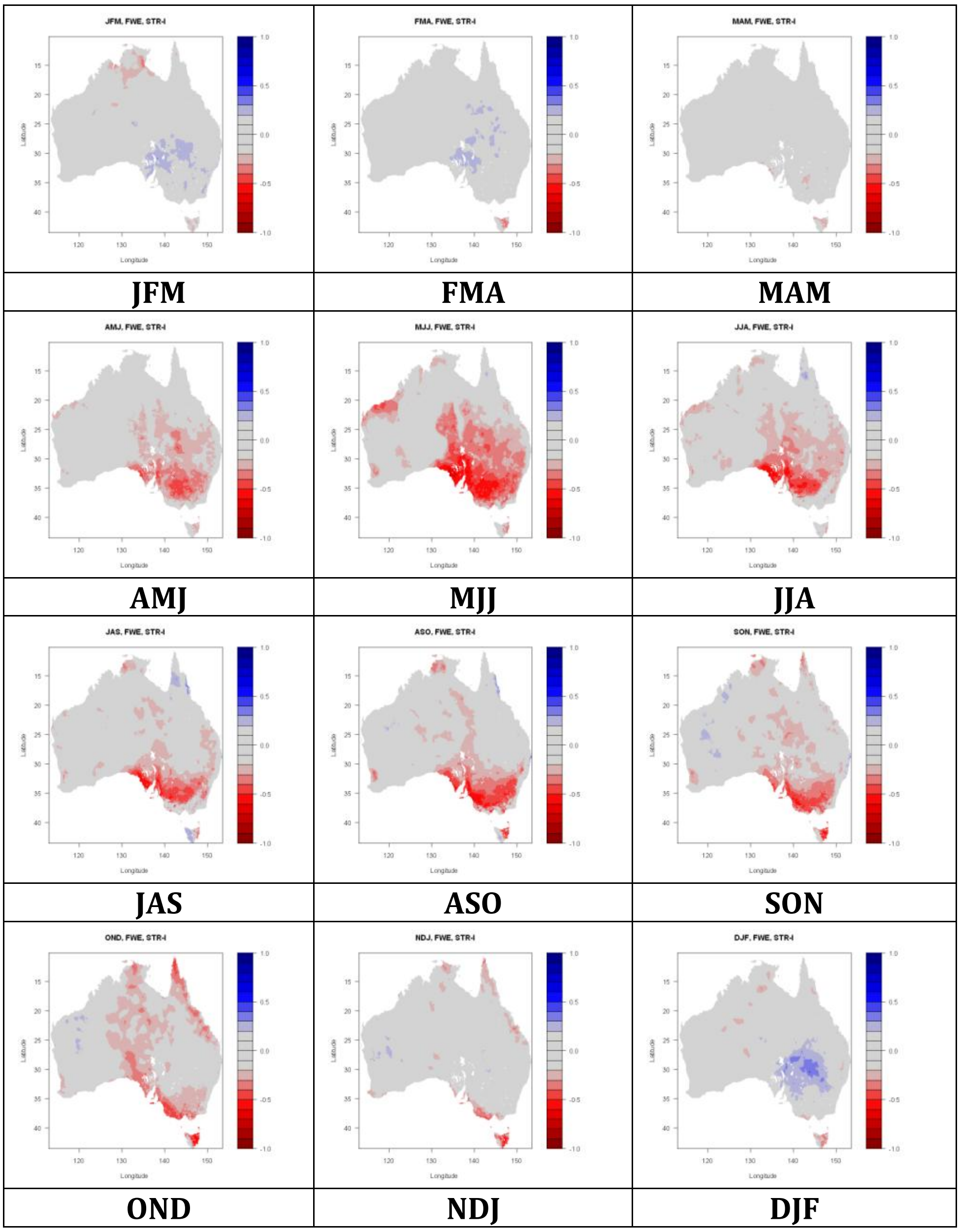
Figure 3: *As per Fig. 1 but for lower soil moisture (0.2 to 1.5m deep).*



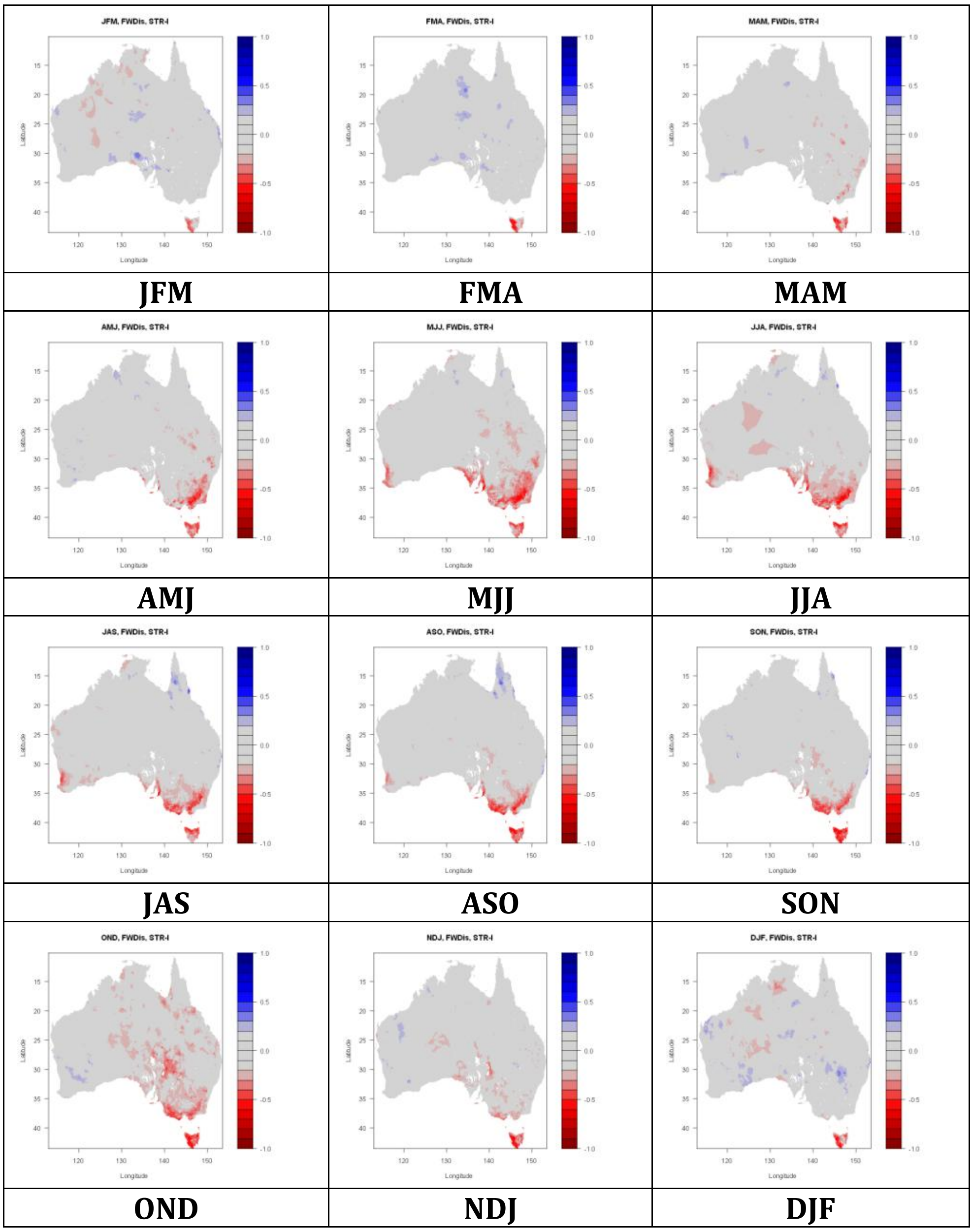
JFM FMA MAM

AMJ MJJ JJA

JAS ASO SON

OND NDJ DJF

Figure 4: *As per Fig. 1 but for total evaporation.*



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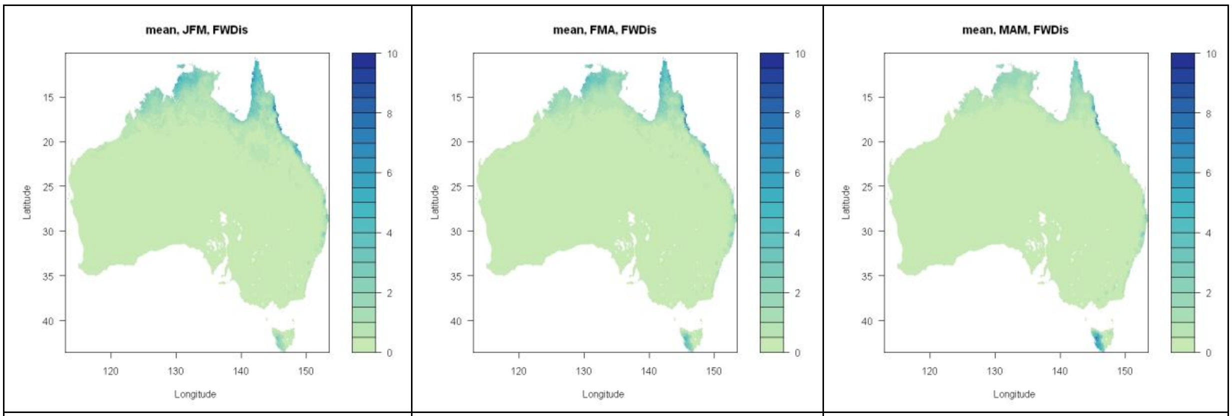
AMJ MJJ JJA

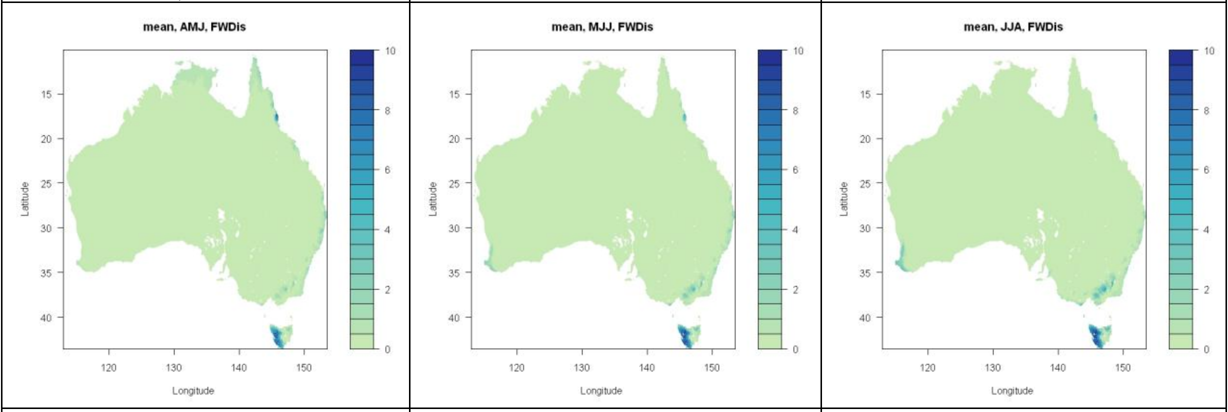
JAS ASO SON

OND NDJ DJF

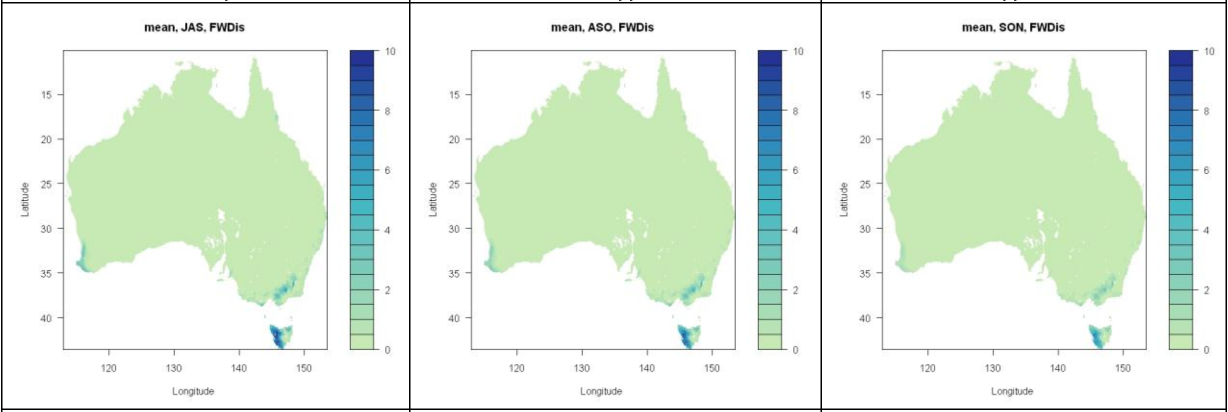
Figure 5: *As per Fig. 1 but for total runoff.*



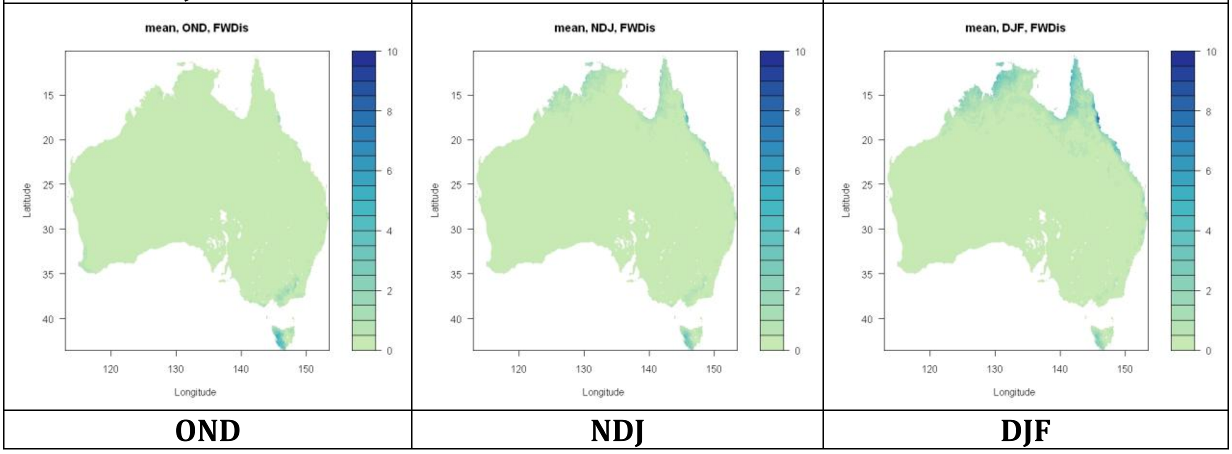
JFM | **FMA** | **MAM**



AMJ | **MJJ** | **JJA**



JAS | **ASO** | **SON**



OND | **NDJ** | **DJF**

Figure 6: *Monthly total runoff (in mm/day) averaged from 1900 to 2007.*

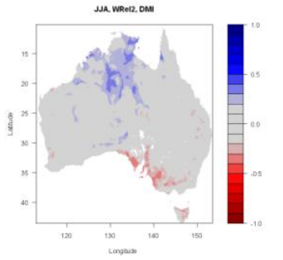
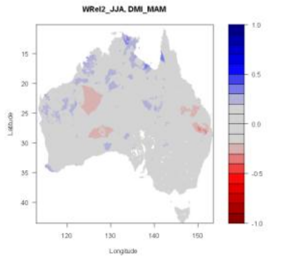
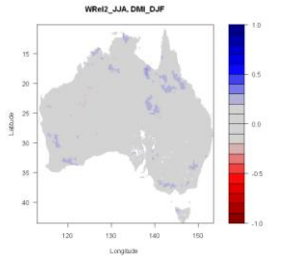
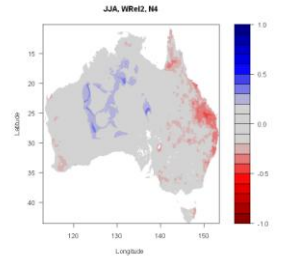
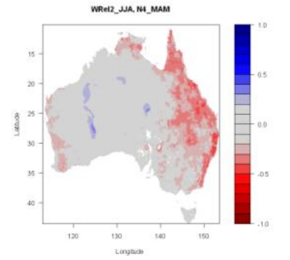
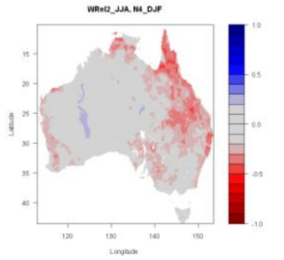
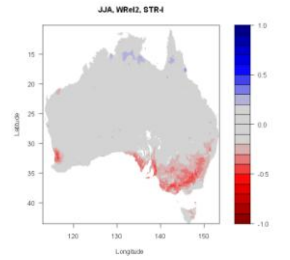
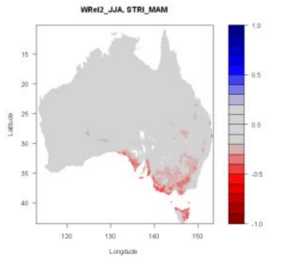
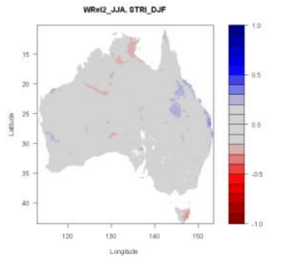
WRel2	Simultaneous (JJA)	3 Month Lag (MAM)	6 Month Lag (DJF)
DMI			
Nino 4			
STR-I			

Figure 7: *Seasonal correlations between various large-scale indices (Nino 4 SST anomalies, the Indian Ocean Dipole Index and the sub-tropical ridge intensity) at lag 0 (left column), at three-month lag (middle column) and at six-month lag (right column) for winter (JJA) lower soil moisture (0.2 to 1.5m deep).*

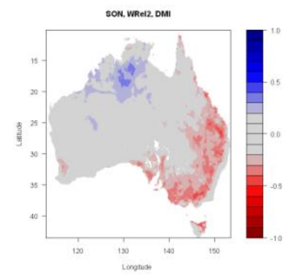
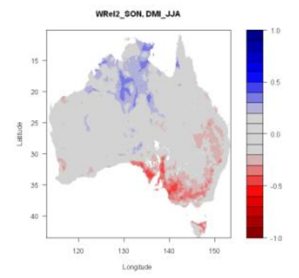
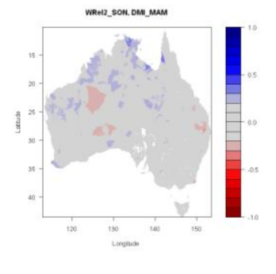
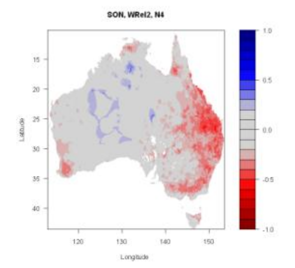
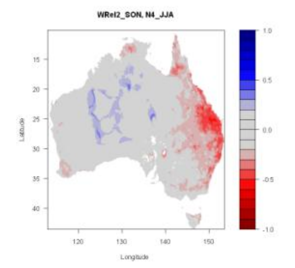
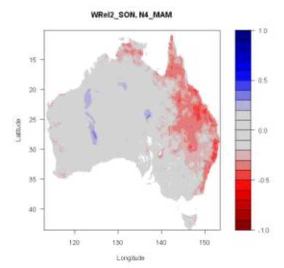
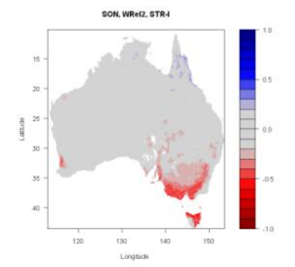
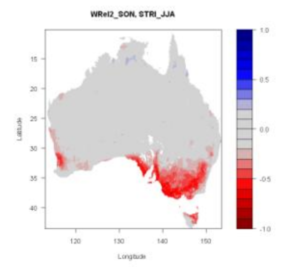
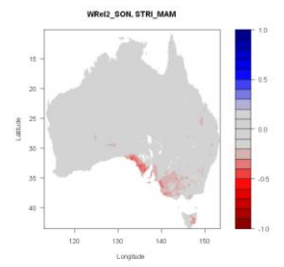
WRel2	Simultaneous (SON)	3 Month Lag (JJA)	6 Month Lag (MAM)
DMI			
Nino 4			
STR-I			

Figure 8: *As per Fig. 7 but for spring (SON) lower soil moisture (0.2 to 1.5m deep).*

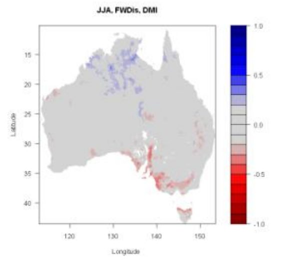
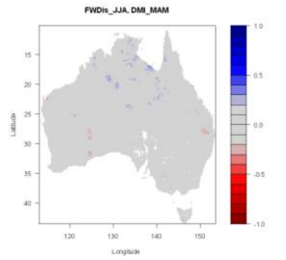
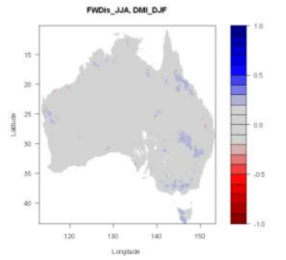
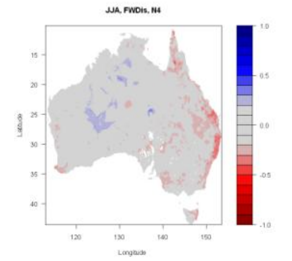
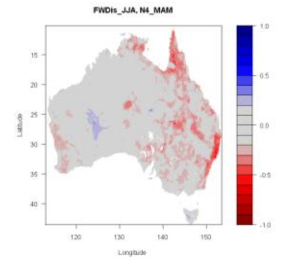
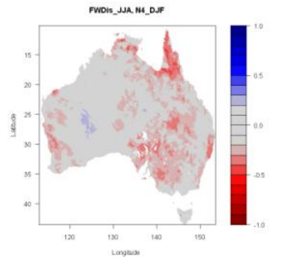
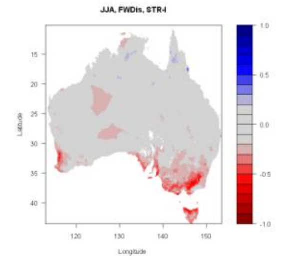
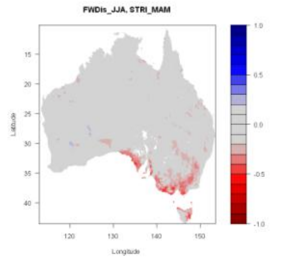
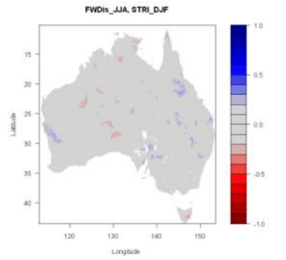
FWDis	Simultaneous (JJA)	3 Month Lag (MAM)	6 Month Lag (DJF)
DMI			
Nino 4			
STR-I			

Figure 9: *As per Fig. 7 but for winter (JJA) runoff and discharge.*

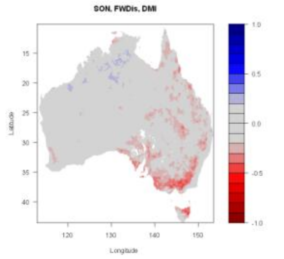
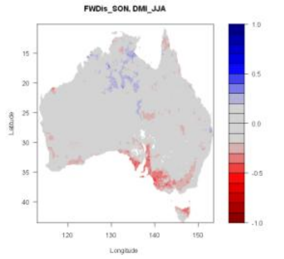
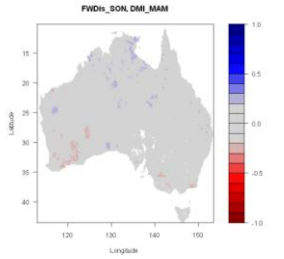
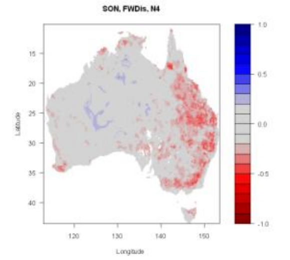
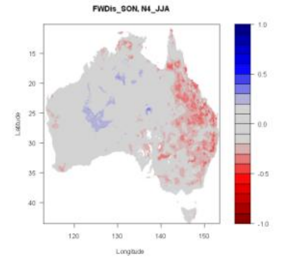
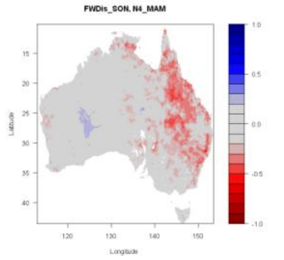
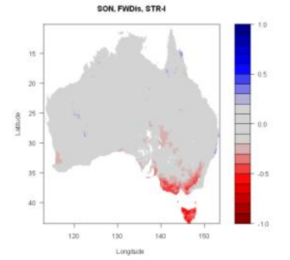
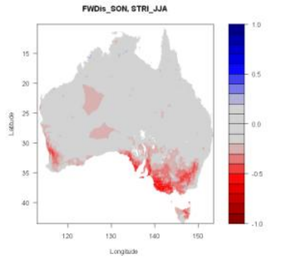
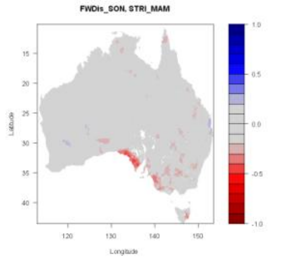
FWDis	Simultaneous (SON)	3 Month Lag (JJA)	6 Month Lag (MAM)
DMI			
Nino 4			
STR-I			

Figure 10: *As per Fig. 7 but for spring (SON) runoff and discharge.*