South Eastern Australian Climate initiative

Final report for **Project 1.3.1P**

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

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Objective:

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

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 the subsequent effect of the recent rainfall decline on other surface water balance variables, and to investigate how the dominant large-scale modes of variability affecting rainfall affect, 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 total runoff decline (on an annual basis).

This has been done by investigating the AWAP variables upper and lower soil moistures, total evaporation and total runoff, and comparing the relationship between these variables and large-scale climate indicators and the same relationships with rainfall, which is the most important atmospheric forcing.

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) in the prior season. This reflects the strong influence of the STR-I on rainfall. 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 total runoff in spring compared to the rainfall reduction in spring (Timbal, 2009) as this would mean that soil moisture levels would be relatively lower than previously and result in relatively less runoff for the same amount of rainfall.

Significant research highlights, breakthroughs and snapshots

This project has highlighted the potential for a more detailed understanding of how the on-going climate change is affecting the entire water balance across SEA. These early results are very encouraging. Further analysis and development using AWAP products are planned as part of the Phase 2 of SEACI, which is expected to help advance our understanding of the water balance across the SEACI area of interest.

Statement of results, their interpretation, and practical significance against each objective

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

- There is a strong consistency in the pattern of the STR-I influence on all related moisture variables for the period – i.e. on rainfall, upper and lower soil moisture, total evaporation and total runoff from around March to October;

- The influence of the STR on rainfall, upper soil moisture and total evaporation is simultaneous. In contrast, both lower soil moisture and runoff show lower correlations with the STR-I in the early part of the wet season (May-June-July), with correlations peaking in the latter part of the wet season (August-September-October);

- The spatial extent of the area having significant correlations between STR-I and deep soil moisture and total runoff is much reduced compared to the area where there are significant correlations between these variables and rainfall, but covers most of the important catchment areas in SEA;

- In contrast to other large-scale influences (El Niño–Southern Oscillation – ENSO and the Indian Ocean Dipole – IOD), the STR intensification is the only variable which exhibits higher lag correlations compared to the simultaneous correlations, in particular with deep soil moisture and runoff; and

- The lag correlation between the STR-I and deep soil moisture and runoff in winter and spring is consistent with the hydrological understanding of the relationship between rainfall and lower soil moisture and run-off but offers a possible additional effect to contribute to the amplification of the rainfall decline in term of impacts on streamflow as the STR intensification is more pronounced in the early part of winter.

Further details are included in the attachment.

Summary of links to other projects

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

1. The detection of climate change across South Eastern Australia (SEA) (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 and 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 SEA (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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Attachment

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

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 give 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 runoff are investigated and compared with rainfall, which is the most important atmospheric forcing.

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%) the rainfall decline occurred in autumn. The annual rainfall decline was large but not unprecedented. However this large rainfall decline combined with the autumn signature, a reduction in the inter-annual variability and higher temperature, was record breaking for water availability (e.g. streamflows) 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) and 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). Rather, 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), which is a manifestation of the intensification of the sub-tropical ridge (STR), could explain up to 70 per cent of the total rainfall decline across SEA (Timbal et al., 2007). Recently, the rainfall decline across SEA has worsened and become the 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 the generation of runoff in SEA (Timbal and Fernandez, 2009).

The Drosdowsky (2005) sub-tropical ridge intensity (STR-I) index was used and its impact on the various moisture variables available from AWAP was evaluated. Correlations between the STR-I and monthly means of AWAP variables for the period from 1900 to 2007 were computed and averaged for 3 monthly periods. These correlations are shown below 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:

- At first order, there is a strong consistency on the pattern of the influence of the STR-I on all related moisture variables, with negative correlations at certain times of the year (generally from about April through November) being apparent across SEA for rainfall, upper and lower soil moisture, evaporation and runoff;

- Beyond the overall consistency which is expected amongst all hydrological variables, differences in spatial patterns and seasonality are worth exploring further;

- There is no lag effect between the influence of the STR-I on 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 mostly the case for total evaporation as well, but differences in the spatial extent of the influence of the STR-I on rainfall versus evaporation suggests that, while the relationship is very similar inland of the Great Dividing Range (GDR) (i.e. suggesting that evaporation is primarily moisture limited), it is not so on the GDR and along the coast, where the relationship between evaporation and the STR-I is negligible, suggesting that daily maximum temperature (which is positively related to the STR-I) is a more important factor;

- Lower soil moisture and runoff show lower correlations with STR-I compared to the other variables. This is particularly noticeable in the early part of the wet season (April-June), but less so in the latter part of the wet season (July to November). This reflects the fact that in the earlier part of the wet season, a greater proportion of any rainfall will go into wetting up the soil moisture store;
- That difference creates a lag effect in term of importance of the STR-I for these two variables compared to rainfall: the largest correlation between the STR-I and deep soil moisture is observed in spring (ASO/SON) while for runoff it is fairly similar during the entire wet season (April to November); and

- The spatial extent of the area of significant correlation between STR-I and deep soil moisture and runoff is smaller than for the area significantly correlated with rainfall, evaporation and upper soil moisture, but covers most of SWEA and the 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 STR-I on all important surface water balance variables available from the AWAP, the lag effect on deep soil moisture and runoff is consistent with the general understanding of the rainfall relationship with deep soil moisture and runoff. This first analysis using the AWAP suite of variables supports the suggestion made earlier in SEACI-1 of the importance of the autumn rainfall decline in contributing to the amplified impacts on streamflows (Murphy and Timbal, 2008) through the linkage back to the primary driver of the rainfall decline (the STR-I). This is worth exploring further. Using the AWAP, we have a tool to investigate the possible lag effect between the rainfall decline (predominantly in autumn) and the impacts on total runoff which are largest in winter and spring.

Lag correlations between large-scale indicators and water balance components

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- 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 in autumn, it is interesting to compare the lag effect of these three indices on those AWAP variables which are showing a tendency to display a lag effect.

The main points to note regarding these correlations for winter (upper parts in Figs 6 and 7) (comparing simultaneous and 3-month lag correlations) are:

- Three-month lag correlations between both N4 and STR-I and lower soil moisture are significant 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 correlations are lower than the simultaneous correlations for the STR-I but higher for N4;

- The DMI has no significant lag correlations anywhere across SEA, which is consistent with the fact that IOD events do not form until winter and do not therefore have a relationship with rainfall in MAM;

- The above findings for lower soil moisture are equally valid for total runoff.

In the case of the spring correlations (lower parts in Figs 6 and 7):

- The DMI has the largest simultaneous correlations of the 3 indices with lower soil moisture, across Australia consistent. This is consistent with the know influence of the IOD across Australia and the fact that it peaks in spring;

- Although all three large-scale indices have lower correlations with total runoff, results are mostly similar, although the STR-I appears more important at lag 0 than the DMI in some parts of the SEA, in particular in southern Victoria;

- 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 correlations are higher;

- These findings reflects the fact that the lag correlations between STR-I and deep soil moisture are larger than the simultaneous one (this is also the case for total runoff);

- Three-month lag correlations with N4 are decrease across SEA towards the eastern seaboard, while simultaneous correlations are significant across large part of SEA including the Great Dividing Range;

- Six-month lag correlations are in most instances insignificant across most of SEA with the exception of N4 along the Eastern seaboard 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 previous seasons. This reflects the strong influence of the STR-I on the rainfall in those earlier seasons (i.e. at lag zero). That lag mechanism is particularly evident in spring when the simultaneous impact of the STR-I on rainfall starts to be reduced but the lag effect between STR-I and deep soil moisture and runoff results is significant. Since during the last decade, the STR intensification has been larger in JJA than in SON (Timbal and Fernandez, 2009) this could contribute to a reduction of the streamflows in spring, a season where rainfall reduction is small (Timbal, 2009), beyond the historical hydrological amplification of the rainfall signal in that season. In turn (and in conjunction with a reduction in the interannual variability of rainfall), this could potentially account for a significant part of the annual amplification of the hydrological response to the rainfall decline.

This early analysis using the AWAP does not permit a definitive answer. Future analysis will need to investigate how the amplification factor between rainfall and runoff has changed seasonally and annually while the autumn rainfall decline has been happening. In particular, future analyses need to look at how those changes in patterns in rainfall (as a result of changes in STR-I) have affected the other moisture variables and relationships between rainfall and the other moisture variables on a seasonal and annual basis.

Conclusions and future perspective

This project has highlighted the potential for better understanding how the on-going climate change is affecting the entire water balance across the SEA. 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. It is clear that using AWAP, it is possible to investigate how changes in the seasonal rainfall patterns have affected changes in seasonal runoff patterns in relationship to marked step change in rainfall and runoff in 1996–1997.

A particular focus will be to use advanced 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). This is 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 states and which combinations of large-scale drivers result in particular hydrological regimes.

A first step will be on investigating how the intensity and position of the STR act together and are associated with rainfall. Based on linear statistics it was shown that the addition of position generally had no additional effect to that of intensity alone (Timbal and Fernandez, 2009). This finding is somewhat surprising and worth investigating further using more advanced 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.

References

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Tables and figures

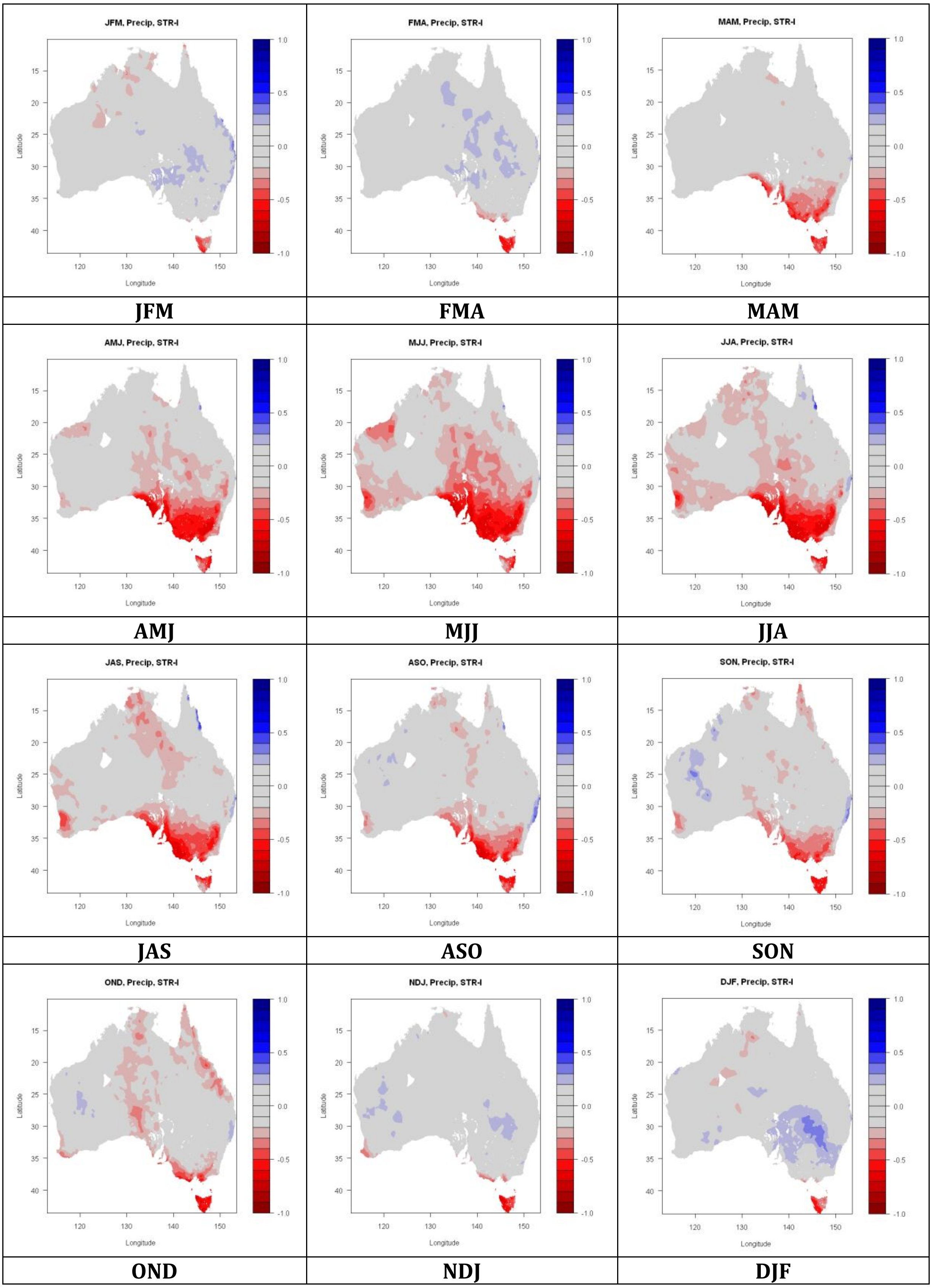

Figure 1: *Month by month, three-month average correlations between the sub-tropical ridge intensity and rainfall across Australia, based on observations from 1900 to 2007; only correlations significant above the 95 per cent level are shown.*

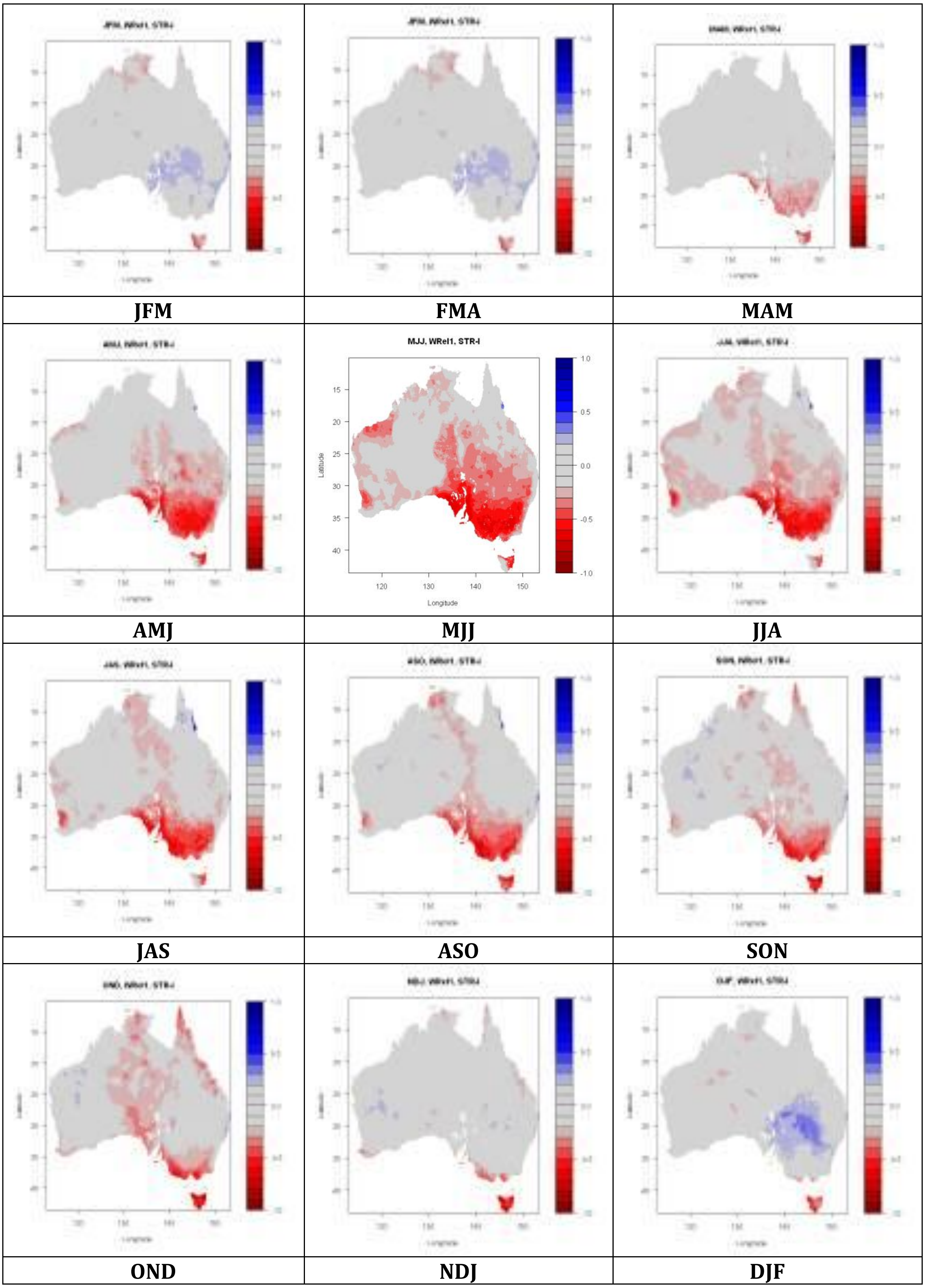

Figure 2: *As per Fig. 1 but for upper soil moisture (20cm deep).[Note a low resolution is used for these maps which are very similar to Fig. 1 to minimize the size of the report].*

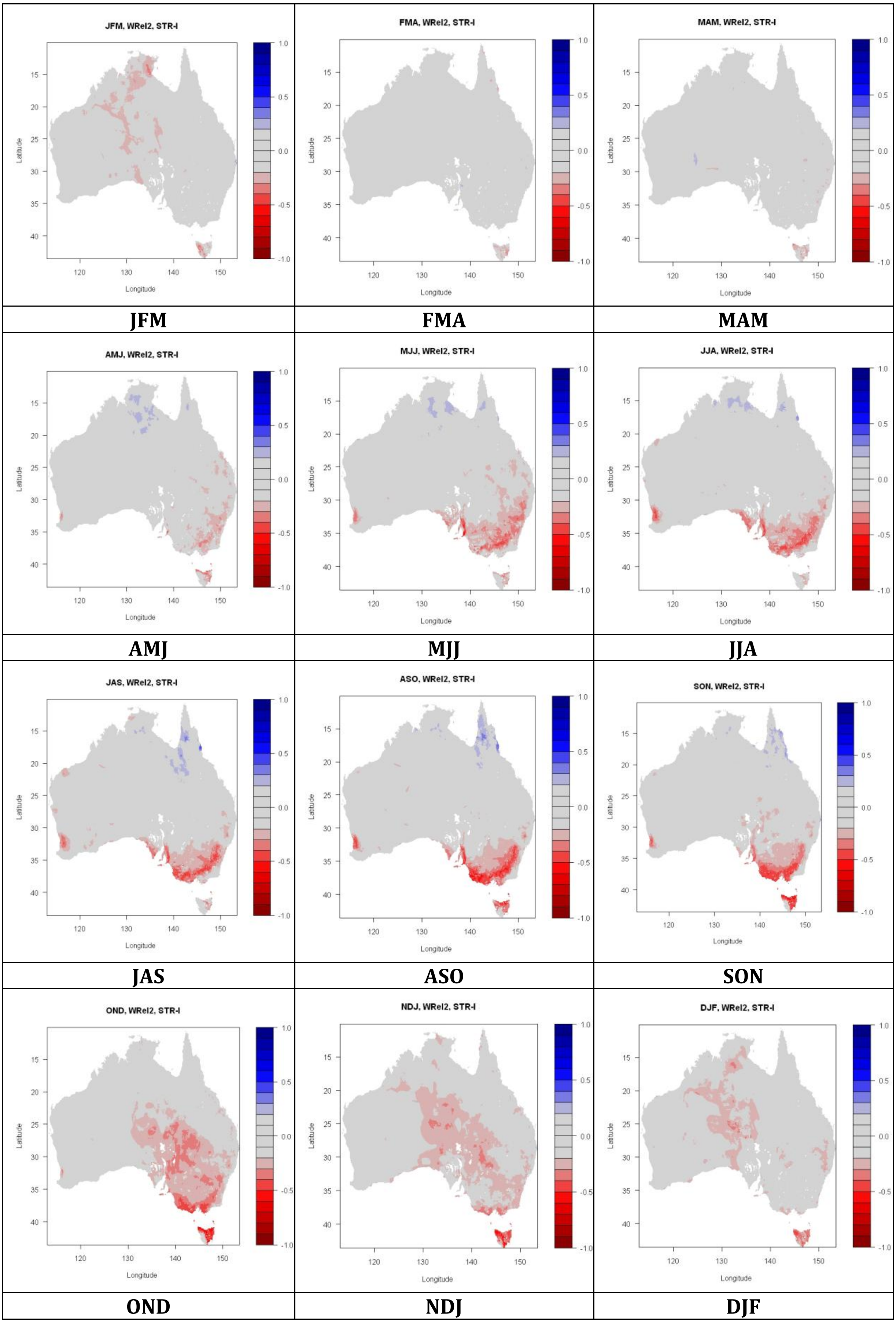

Figure 3: *As per Fig. 1 but for lower soil moisture (0.2 to 1.5 m deep).*

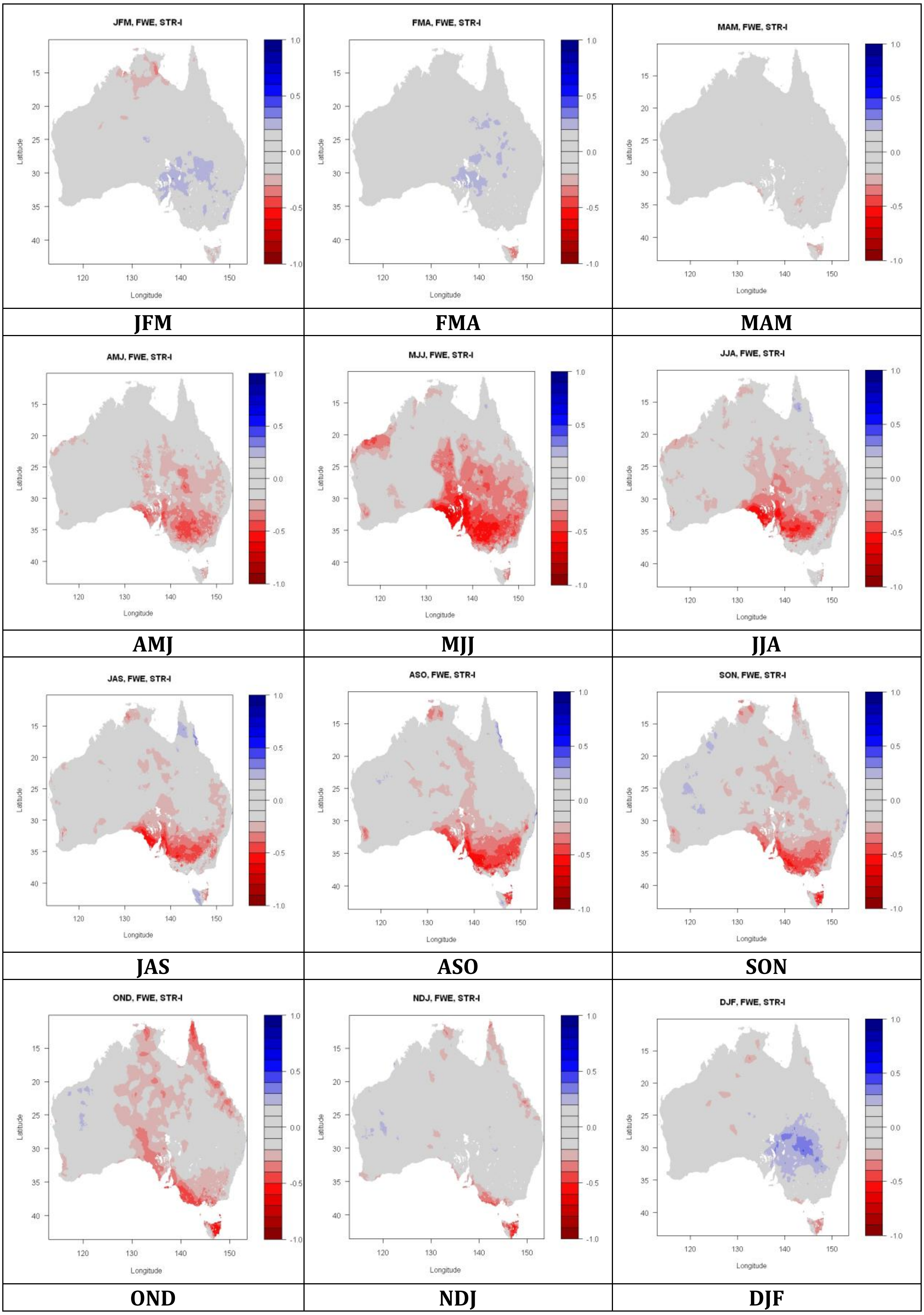

Figure 4: *As per Fig. 1 but for total evaporation.*

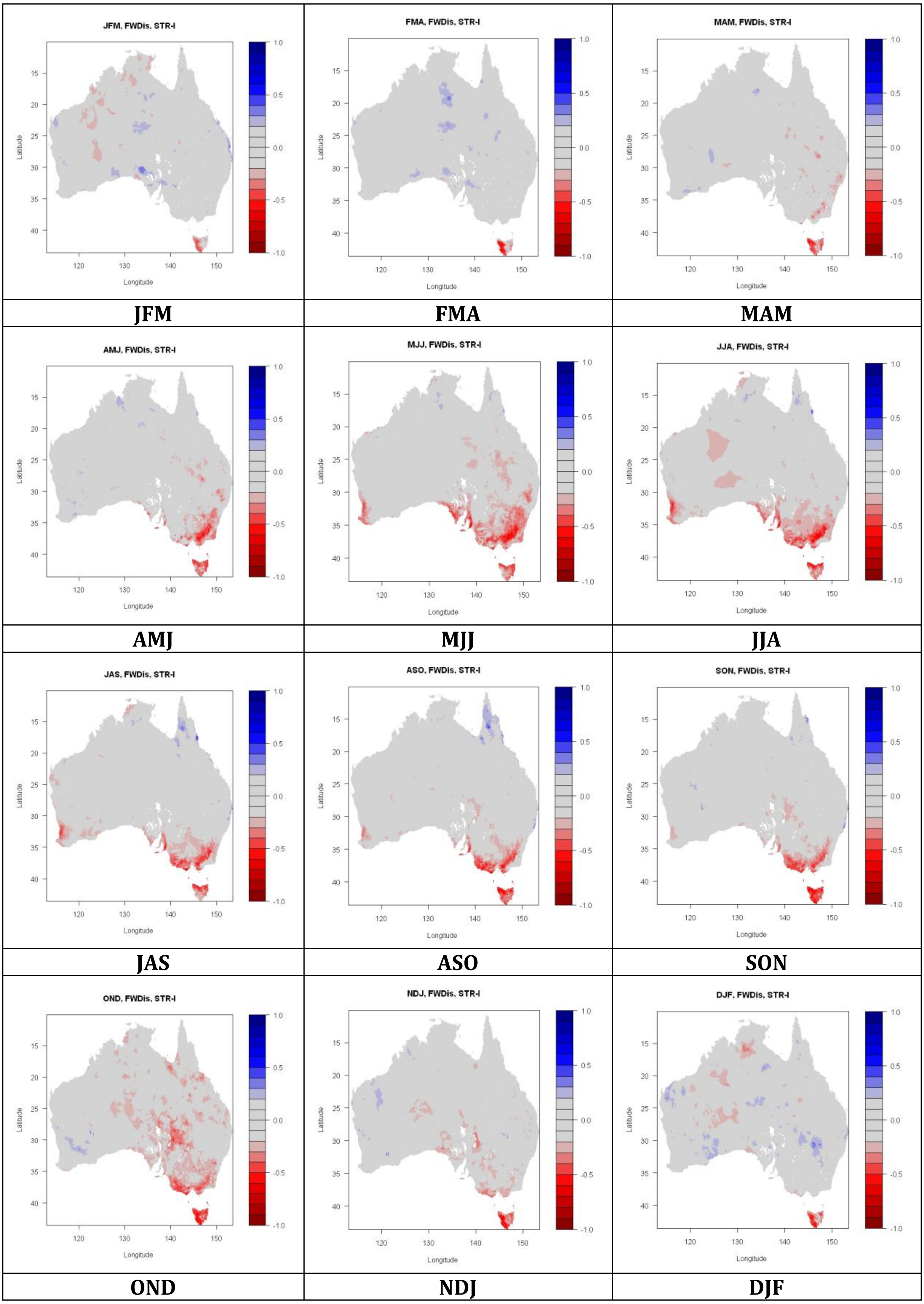

Figure 5: *As per Fig. 1 but for total runoff.*

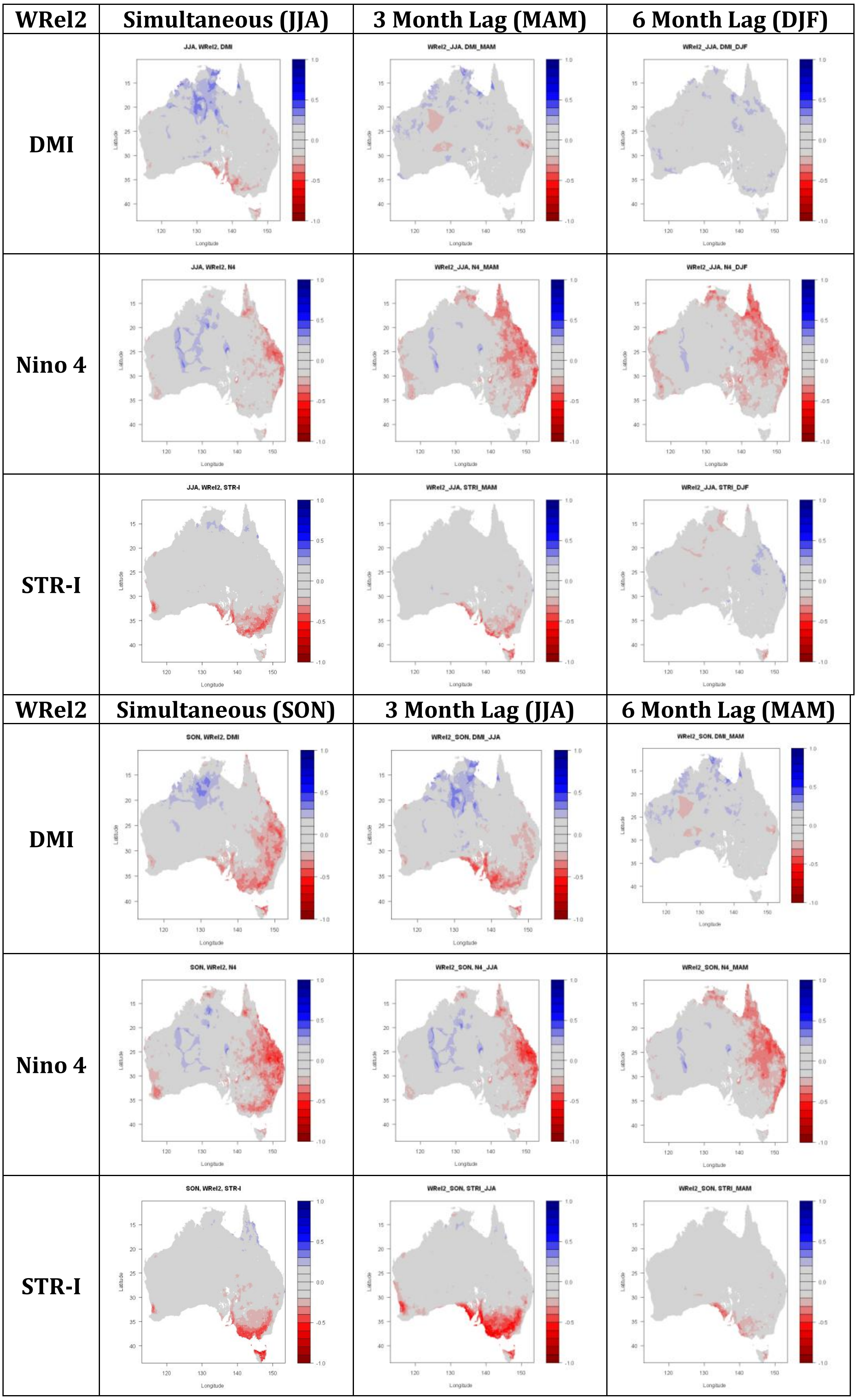

Figure 6: *Seasonal correlations between various large-scale indices (Nino 4 SST anomalies, the Indian Ocean Dipole Index and the sub-tropical ridge intensity) at lag 0 (left column), at three-month lag (middle column) and at six-month lag (right column) for winter (top maps) and spring (lower maps) lower soil moisture (0.2 to 1.5m deep).*

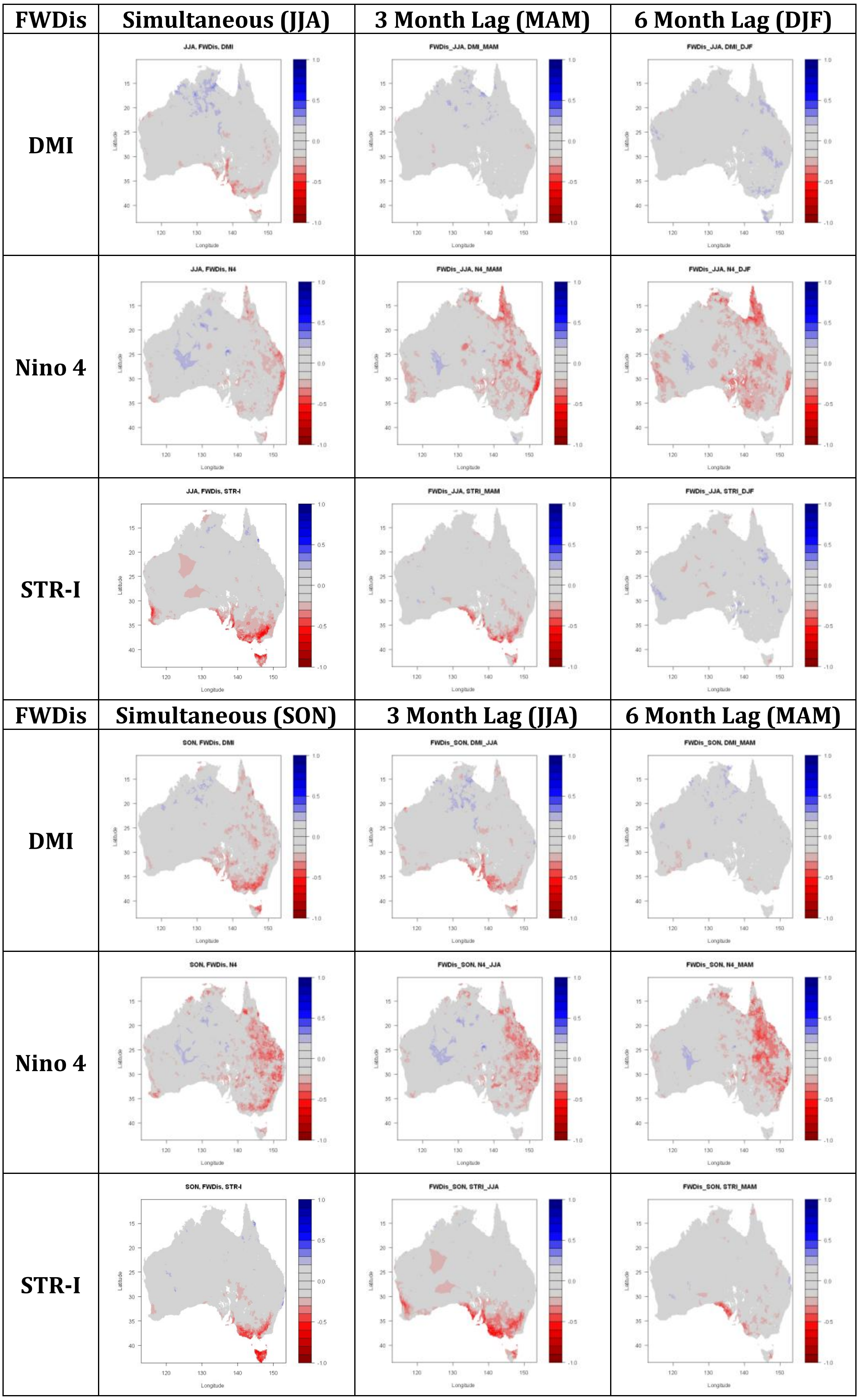

Figure 7: *As per Fig. 6 but for runoff and discharge*