

CHAPTER 4: PROJECT 1.2

Impact of climate variability and change on the water balance

Michael Raupach, Peter Briggs, Vanessa Haverd, Kirien Whan and Caroline Ummenhofer

Abstract

- The Australian Water Availability Project (AWAP) hydrometeorological dataset has been recomputed with new (V3) meteorological data, revealing a significant (10 to 20 percent) decrease in Murray–Darling Basin (MDB) total runoff in the later part of the 20th century relative to the runoff from the earlier (V1) meteorological data.
- The AWAP dataset has been used to find a distinct asymmetry in the impacts of opposite phases of both El Niño – Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) on Australian hydrology, and significant differences between the dominant drivers of drought at inter-annual and decadal timescales.
- Continental correlation maps between AWAP water-balance properties (rainfall and upper-layer soil moisture) and climate indices (the tripole index and the indices for ENSO and IOD) show that the tripole has the largest association with rainfall and soil moisture.

Background

The aim of the Australian Water Availability Project (AWAP) is to monitor the state and trend of the terrestrial water balance of the Australian continent, using model-data fusion methods to combine both measurements and modelling. The project determines the past history and present state of soil moisture and all water fluxes contributing to changes in soil moisture (rainfall, transpiration, soil evaporation, surface runoff and deep drainage), across the entire Australian continent at a spatial resolution of 5 km. Using the same basic framework, the project provides soil moistures and water fluxes over the Australian continent in three forms: (1) weekly near-real-time reporting, (2) historical monthly time series (1900 to present), and (3) monthly climatologies.

Past work in the Australian Water Availability Project (AWAP) has provided a 109-year (1900–present and ongoing) record of soil moisture and all terrestrial water fluxes over the Australian continent at 5-km spatial and daily temporal resolution (with monthly archive). This record has been validated by extensive testing against streamflow records from unimpaired gauged catchments – a sensitive test. This record provides an opportunity to better understand the relationships between climate and the terrestrial water balance, the current decreases in water availability, and the skill of prediction schemes when run in hindcast (i.e. retrospective) mode.

Objectives

The research in Project 1.2 falls into three main categories.

Australian Water Availability Project gridded hydrometeorological data

The objectives were to:

- produce time series of hydrological responses (soil moisture, runoff components, evaporation components) and proximate meteorological forcing variables (including rainfall, solar radiation and temperatures) over a limited set of test hydrological units (catchments, basins or grid cells) in south-eastern Australia (SEA), using the AWAP dataset
- ensure continuing flow of updated forcing data and model outputs to other projects in Phase 2 of SEACI, specifically Project 1.1 and Project 3.1, including Waterdyn code enhancements, data quality assessments, model reruns, and maintenance of webpages and ftp sites.

Statistical analysis of climate–water relationships

The objectives were to:

- assemble full data on indices for climate drivers (ENSO, IOD, the Southern Annular Mode (SAM), the sub-tropical ridge (STR), etc.), using websites, colleagues and other sources
- perform collaborative statistical analysis (with the University of New South Wales Climate Change Research Centre (UNSW CCRC)) of ENSO, IOD, rainfall, and AWAP soil moisture results to characterise inter-annual and inter-decadal signals in rainfall and soil moisture in SEA, and their implications for drought persistence and severity in SEA. We supplied AWAP data to UNSW CCRC colleagues, who were consulted and advised and who will be assisting in the production of a collaborative paper on the role of IOD and ENSO in droughts in SEA.

Multi-index statistical model for climate–water relationships

The objectives were to:

- create a general form for a statistical model (possibly non-linear) that relates water-balance responses over an arbitrary spatial domain (grid cell, catchment or basin) to a set of climate indices
- determine the parameters in the statistical model, using a trial set of water-balance properties over a limited set of small test catchments in SEA. This will include determination of confidence intervals, goodness of fit, explained variance and metrics of model skill. Parameter estimation methods will be selected according to the form of the statistical model from available linear and non-linear options.

Results

Australian Water Availability Project gridded hydrometeorological data

The major output from this part of the project in 2009/10 has been the successive incorporation of two improved versions (V2 and V3) of the Bureau of Meteorology (BoM) National Climate Centre (NCC) gridded meteorological data for rainfall, solar radiation and temperature. These update the V1 dataset (Jones et al.,

2007) used in earlier CSIRO AWAP work (Raupach et al., 2009; King et al., 2009) and also in associated projects in Phase 2 of SEACI up to this time. The V3 data (Jones et al., 2009) became available in February 2010, and are regarded by BoM-NCC as the first fully-supported product. There are significant differences between V1 and V3 datasets, including changes to rainfall and temperature surfaces associated with improved interpolation methods and station datasets in V3, and also differences in the treatment of no-data areas.

We have compared the V3 and V1 datasets carefully. The following examples use a sub-division of the Murray–Darling Basin (MDB) by rainfall: wet, moderate and semi-arid sub-divisions have a mean annual rainfall of >1,000 mm, 1,000 to 450 mm, and <450 mm respectively.

- Figure 20 shows an increase in the drying trend (V3 minus V1) in the MDB between the first and second half of the previous century. In wetter (higher altitude) areas (blue) the differences are positive pre-1945 and negative post-1955, indicating a greater drying trend in the new data compared to the old data. New data in agriculturally suitable areas (green) also show a decrease in the second half of the century compared with the original data.
- Figure 21 shows that this difference leads to a 10 to 20 percent decrease in AWAP estimates of annual local discharge or total runoff (defined as the sum of surface runoff and deep drainage) in the second half of the century, when V3 rainfall data are used.

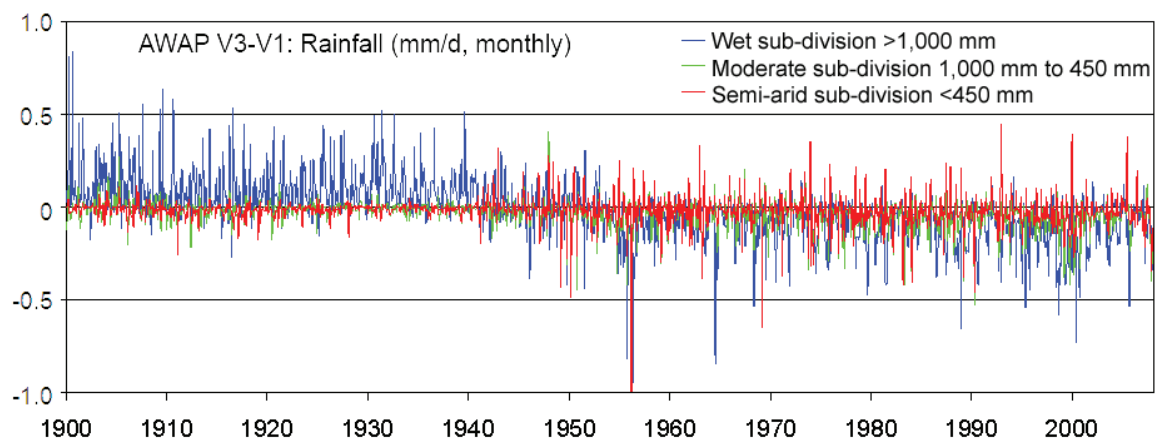


Figure 20. Monthly time series of differences in rainfall (mm/d) between two versions of the Bureau of Meteorology Australian Water Availability Project datasets (V3 minus V1) for three sub-divisions of the Murray–Darling Basin by rainfall

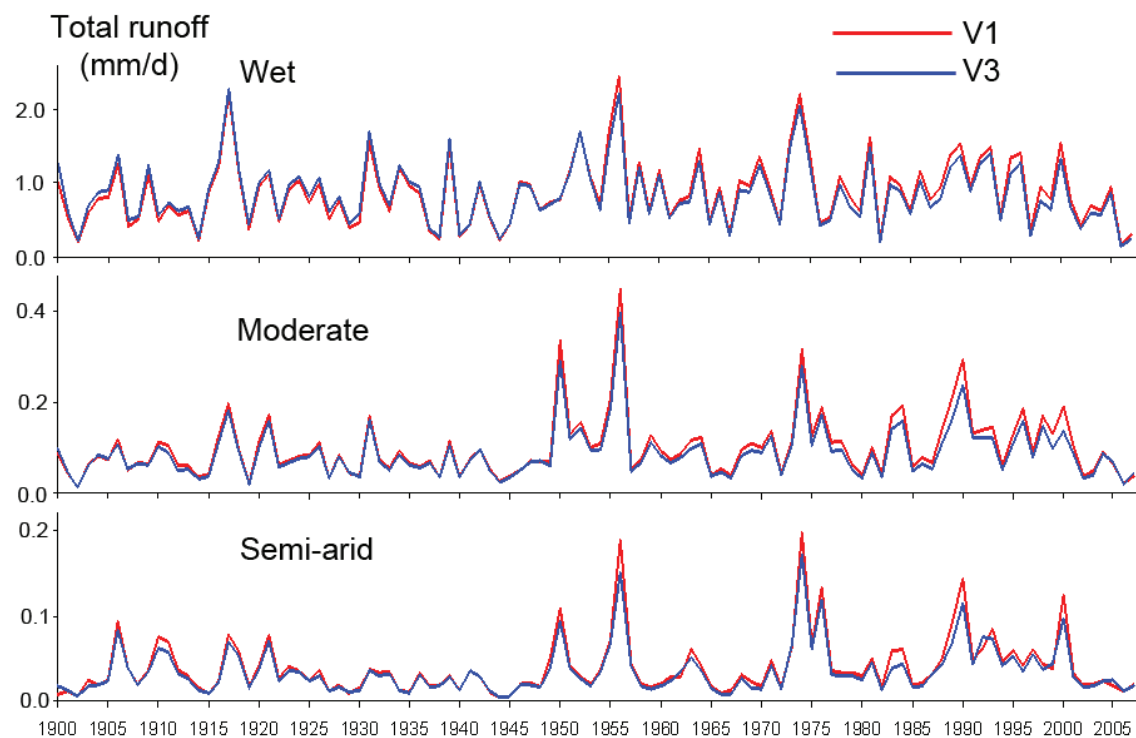


Figure 21. Annual Australian Water Availability Project total runoff (local discharge, in mm/d) for three sub-divisions of the Murray–Darling Basin by rainfall

The differences indicated above have meant that it has been necessary to repeat analyses for several products described later, including the basic AWAP hydrometeorological dataset; statistical analyses of climate–water relationships (Ummenhofer et al., in press; PhD work by Kirien Whan); and work with the CABLE model (Vanessa Haverd).

All other components of the tasks related to data collection have been completed, including:

- assembly of full data on climate indices
- preparation of V3 forcing meteorology
- new runs of AWAP WaterDyn for the continental spatial domain, including a 110-year spin-up for initialisation (Run 26b) and full 1900–2009 historical series with monthly outputs (Run 26c)
- time series of hydrological responses (soil moistures, runoff components, evaporation components) and proximate meteorological forcing variables (rainfall, solar radiation, temperatures, etc.) over a limited set of test hydrological units in SEA
- completion of regionally averaged monthly series (1900–2009) for unimpaired catchments
- assembly of river flow data for major Australian catchments towards attribution of reasons for the current major decreases in water availability and streamflow using AWAP data and the flow cascade approach.

Statistical analysis of climate–water relationships

Indian and Pacific ocean influences on south-eastern Australian drought and soil moisture (with Caroline Ummenhofer (UNSW) and others)

A collaboration with Caroline Ummenhofer and other colleagues from UNSW and CSIRO Marine and Atmospheric Sciences (Ummenhofer et al., in press) has applied AWAP data to increase understanding of the climate drivers of the water balance in SEA, particularly with respect to long periods of drought. This work is

an important precursor to the statistical modelling work that is being developed in this project (see subsequent section on the multi-index statistical model for climate–water relationships). In this work the relative influences of Indian and Pacific ocean modes of variability were investigated for seasonal, inter-annual and decadal timescales. For the period 1900–2006, observations, reanalysis products, and modelled AWAP soil moisture during the cool season were used to assess the impact of ENSO and the IOD on the MDB. Significant findings include:

- Opposite phases of both ENSO and IOD show a distinct asymmetry in their impact on Australian hydrology.
- The dominant drivers of drought differ significantly between inter-annual and decadal timescales. On inter-annual timescales, SEA soil moisture is modified by both ENSO and IOD: wettest conditions are observed during years with a La Niña co-occurring with a negative IOD event, while driest conditions occur in years when an El Niño event coincides with a positive IOD event (Figure 22). The atmospheric circulation associated with these responses is discussed in Ummenhofer et al. (in press). However, decadal variability over SEA including multi-year drought periods, was found to be more robustly related to Indian Ocean temperatures than Pacific conditions.
- During extended periods of drought, the frequencies of both negative and positive IOD events differ significantly from those during prolonged periods of ‘normal’ rainfall. More than 75 percent of all negative IOD events occur during prolonged wet periods. Conversely, no negative IOD years are recorded during droughts; instead, 60 percent of positive IOD events occur during these times. The frequency of ENSO events, in contrast, does not change.
- For the more extensive MDB, however, the impacts of La Niña become more prominent, with 63 percent of wet years occurring during a La Niña phase.
- Across the different categories of ENSO and IOD events, anomalies along the eastern seaboard (i.e., to the east of the Great Dividing Range) are not consistent with those of the wider eastern Australian region. Regional circulation patterns independent of ENSO and IOD seem to dominate rainfall along the eastern seaboard.
- The non-linearity between opposite phases of ENSO and IOD raises important issues for the techniques employed to investigate dominant drivers of climate variability on decadal to longer-term timescales.

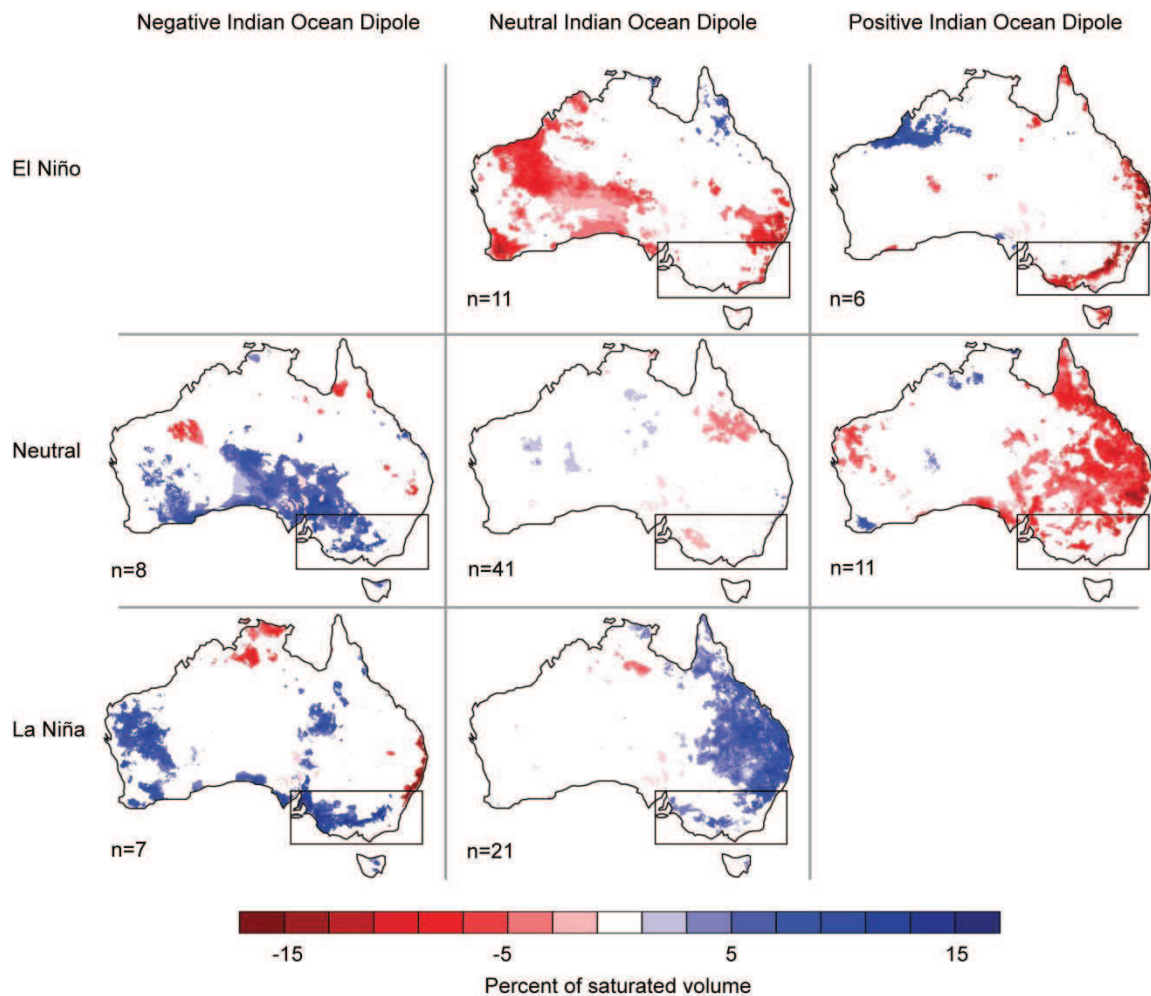


Figure 22. Composite of Australian Water Availability Project lower-layer soil-moisture anomalies in the different El Niño – Southern Oscillation and Indian Ocean Dipole categories: El Niño; La Niña; and positive or negative Indian Ocean Dipole. The number of members (n) in each category are indicated. Anomalies are for the June to October months over the period 1900–2006. The only anomalies that are shown are those which are significant at the 80 percent confidence level as estimated by a two-tailed t-test. Figure adapted from Ummenhofer et al., (in press)

Australian hydroclimatic response to tropical variability

This work focused on the seasonal correlations between climate modes (IOD, ENSO, the tropical sea-surface temperature (SST) tripole index of Timbal et al. 2010) and hydrological responses on the Australian continent as captured in the AWAP dataset. Originally completed using V1 products, this work is currently being reanalysed using V3 in preparation for publication as 'The Australian hydroclimatic response to tropical variability'.

Two sample results are provided. Figure 23 shows the zero-lag monthly correlation patterns between three climate modes (ENSO, IOD and the tripole index) and upper-layer soil moisture and rainfall in winter (Jun-Jul-Aug). For each climate mode, the correlation patterns with rainfall and upper-layer soil moisture are very similar. Precipitation recharges the upper layer of soil almost instantly, with any differences between precipitation and upper-layer soil moisture due to evaporation (driven by temperature) taking place before recharge. Due to the use of northern Australian SST in its definition, the tripole has the largest association with precipitation. Figure 24 shows correlations between rainfall and large-scale modes of variability in both winter and spring, as these are the seasons when tropical variability is the most active.

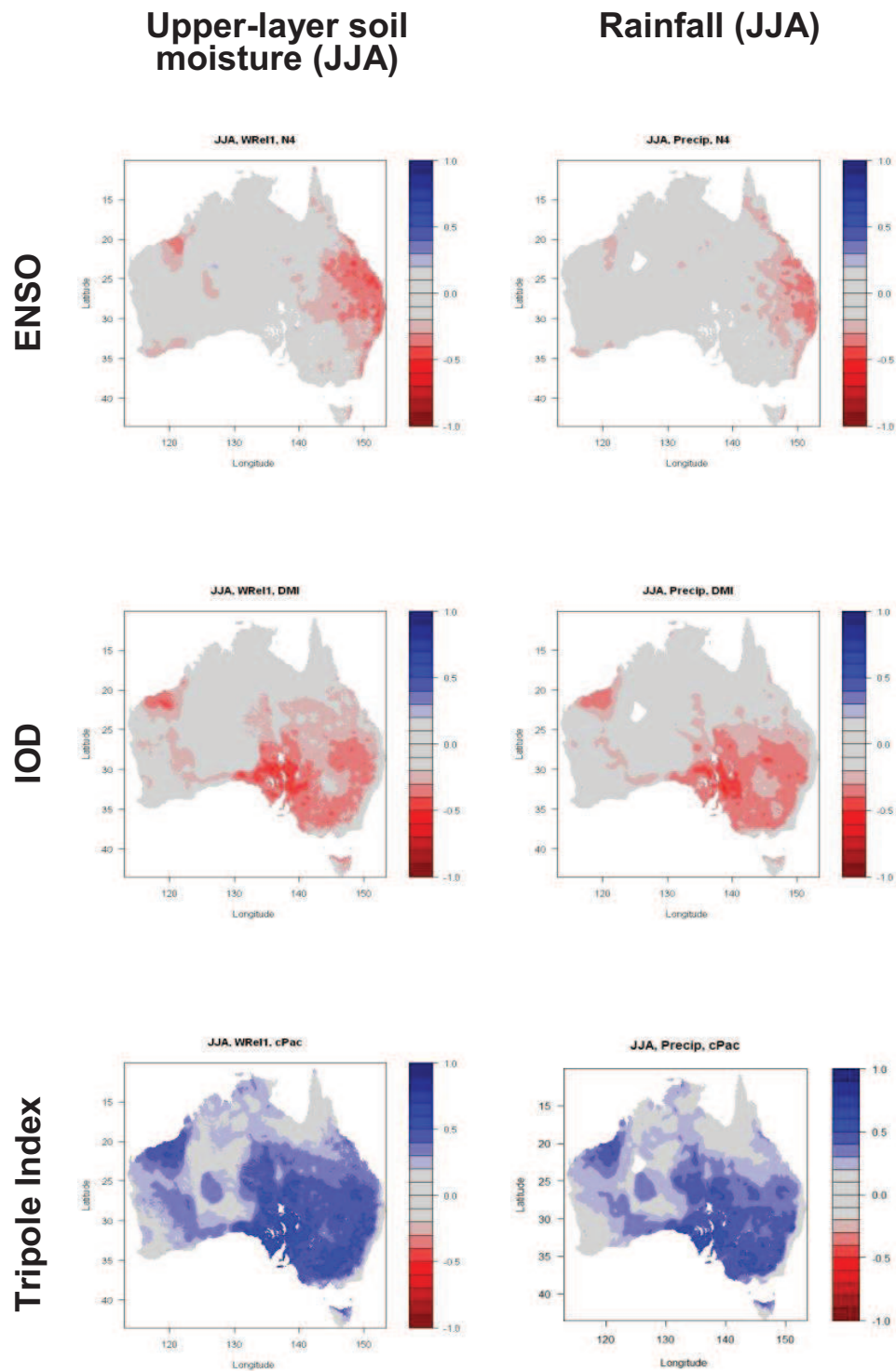


Figure 23. Zero-lag correlations between monthly winter (Jun-Jul-Aug) upper-layer soil moisture and rainfall with El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the tripole index

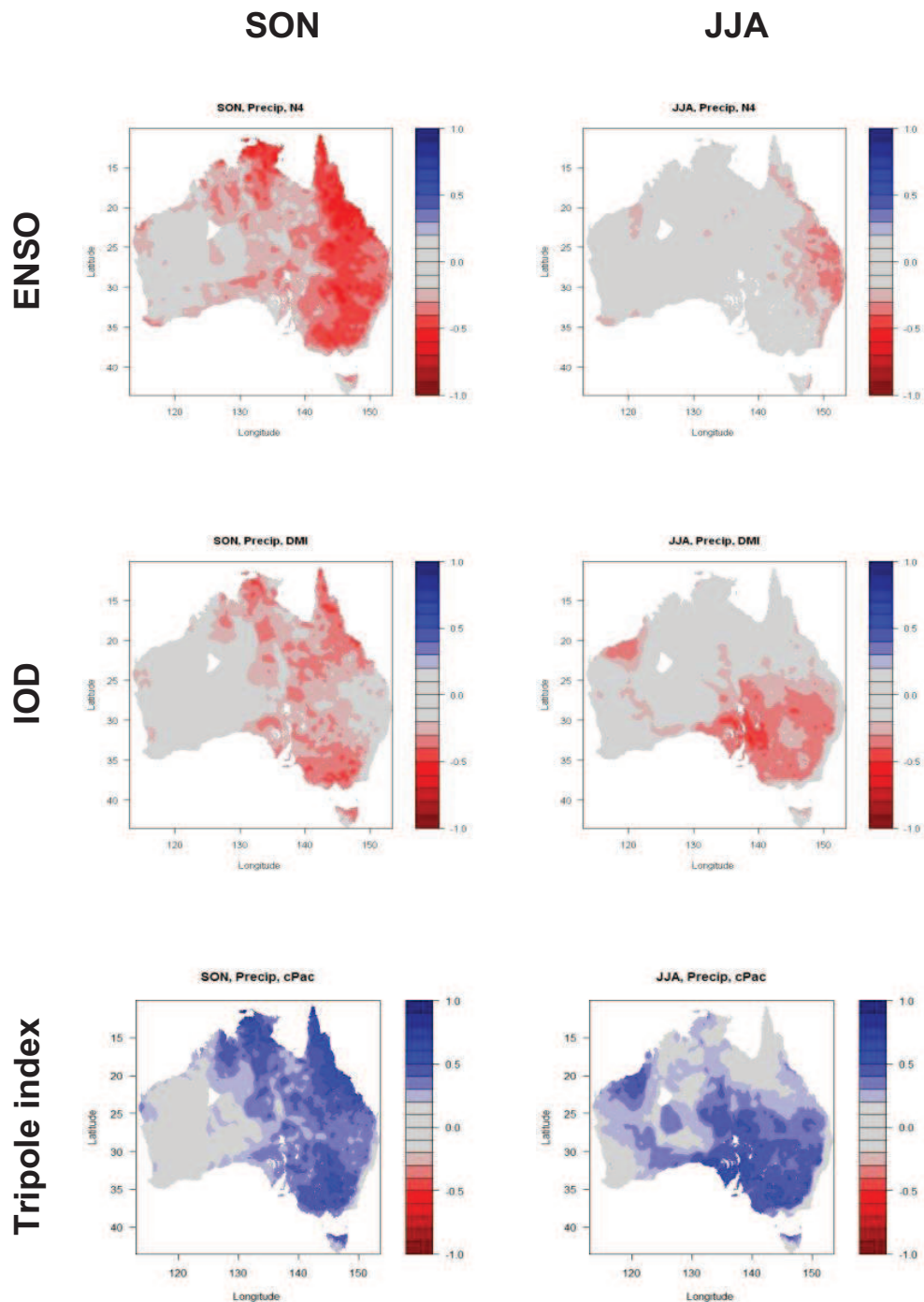


Figure 24. Simultaneous correlations between rainfall and indices for three modes of tropical sea-surface temperature variability: El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the tripole index. Results are shown for winter (Jun-Jul-Aug) and spring (Sep-Oct-Nov), as these are the seasons when tropical variability is the most active. Due to the use of northern Australian sea-surface temperature in its definition, the tripole index has the largest association with rainfall

Multi-index statistical model for climate–water relationships

Here we describe the formulation of a statistical model that relates a set of water-balance responses to a set of climate indices.

The set of water-balance responses is drawn from both hydrological responses (soil moistures, runoff components, evaporation components) and proximate meteorological forcing variables (rainfall, solar

radiation, temperatures, etc.). The set of climate indices includes those for ENSO, IOD, SAM, STR, etc. Model parameters are determined by statistical fitting.

The general linear relationship between a single-point water-balance property $w(t)$ (e.g. rainfall, soil moisture, total runoff) and a set of N climate modes $a_n(t)$ (e.g. ENSO, IOD, STR) is:

$$w(t) = \sum_{n=1}^N x_n a_n t$$

where x_n is a set of N weights which constitute the model parameters. Considering this relationship across a set of M spatial points, this relationship can be written in the vector-matrix form:

$$\begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_M \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ \vdots & \vdots & \vdots \\ a_{M1} & a_{M2} & a_{M3} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

or:

$$\mathbf{w} = \mathbf{A} \cdot \mathbf{x}$$

where the column vector \mathbf{w} is a time series of M values of a local water-balance property, the matrix \mathbf{A} is a set of time series of climate indices ($M \times N$), and the column vector \mathbf{x} is a set of N parameters. Typically we have $M \approx 1,000$ and $N \approx 3$.

The problem is to find the parameters \mathbf{x} , given climate indices \mathbf{A} and the water-balance property \mathbf{w} . This is done by minimising:

$$\text{Error}^2 = \mathbf{w} - \mathbf{A}\mathbf{x}^T \mathbf{w} - \mathbf{A}\mathbf{x}$$

This problem has an analytic solution which can be found by several methods and can be expressed in several equivalent ways:

1. Solution by variation yields:

$$\mathbf{x} = \mathbf{A}^T \mathbf{A}^{-1} \mathbf{A}^T \mathbf{w}$$

2. An alternative expression can be obtained using the singular value decomposition of \mathbf{A} :

$$\mathbf{A}_{M \times N} = \begin{pmatrix} \mathbf{U} \\ M \times M \\ \text{column-} \\ \text{orthonormal} \end{pmatrix} \begin{pmatrix} \mathbf{W} \\ M \times N \\ \text{diagonal} \end{pmatrix} \begin{pmatrix} \mathbf{V}^T \\ N \times N \\ \text{column-} \\ \text{orthonormal} \end{pmatrix}$$

This approach yields an equivalent expression for \mathbf{x} :

$$\mathbf{x} = \mathbf{V}\mathbf{W}^{-1}\mathbf{U}^T\mathbf{w}$$

3. We can form the correlation vector \mathbf{b} ($N \times 1$) between the climate indices and water-balance property \mathbf{w} , and also the correlation matrix \mathbf{C} ($N \times N$) between climate indices:

$$\mathbf{C} = \mathbf{M}^{-1}\mathbf{A}^T\mathbf{A}, \quad \mathbf{b} = \mathbf{M}^{-1}\mathbf{A}^T\mathbf{w}$$

Figure 23 shows spatial maps of components of \mathbf{b} for the set of climate indices (the tripole index and the indices for ENSO and IOD). In terms of these quantities, the solution for the parameters \mathbf{x} is:

$$\mathbf{x} = \mathbf{C}^{-1}\mathbf{b}$$

Any of the mathematically identical forms (1), (2) and (3) constitutes the analytic solution for the statistical model $\mathbf{w} = \mathbf{A}\mathbf{x}$. We note that:

- The model as described above is for a single point. Large-scale (e.g. Australian continent) application is simply a question of applying this model repeatedly for water-balance time series \mathbf{w} in different cells (there are about 278,000 0.05 degree cells in the continental AWAP dataset). The result is a set of N parameters \mathbf{x} in each cell ($N = 3$ for three climate indices) which give the weights describing the relationship between the water-balance property and multiple climate indices.
- Solution for model parameters \mathbf{x} can be done analytically in the linear version described here (that is, without searching numerically for a minimum in model-measurement squared differences). This makes the model very fast to apply.
- The model can be generalised to allow properties such as time lags and threshold effects to emerge from fitted parameters rather than being externally imposed *a priori*. In this case the matrix \mathbf{A} is a matrix of non-linear functions of climate indices, and the parameters of the non-linear functions have to be found by numerical minimisation of the squared error given above.

This model, developed in 2009/10, will be applied and tested in 2010/11.

Conclusions

- The AWAP hydrometeorological dataset has been recomputed with new (V3) meteorological data, revealing a significant (10 to 20 percent) decrease in MDB total runoff in the later part of the 20th century relative to the runoff from the earlier (V1) meteorological data.
- The AWAP dataset has been used to find a distinct asymmetry in the impacts of opposite phases of both ENSO and IOD on Australian hydrology, and significant differences between the dominant drivers of drought at inter-annual and decadal timescales (Ummenhofer et al., in press).
- Continental correlation maps between AWAP water-balance properties (rainfall and upper-layer soil moisture) and climate indices (the tripole index and the indices for ENSO and IOD) show that the tripole has the largest association with rainfall and soil moisture.

Links to other projects

In 2009/10, Project 1.2 supplied AWAP data to and collaborated with Project 1.1b on the association between global warming and declining soil moisture and runoff (Cai et al. 2009a), and on the link between positive IOD events and bushfires (Cai et al. 2009b). A collaboration with Caroline Ummenhofer and other CMAR and UNSW colleagues has applied AWAP data to increase understanding of the climate drivers of the water balance in south-eastern Australia, particularly with respect to long periods of drought. These results are reported here and in Ummenhofer et al. 2010. Including SEACI projects, the growing AWAP data user list consists of over 90 people representing 32 government, university, and industry bodies, involving over 60 active, completed, or proposed projects. Three quarters of these activities involve the use of CSIRO AWAP model products separately or in conjunction with Bureau of Meteorology (BoM) AWAP meteorology. With the support of SEACI, AWAP model results are made available to the Australian community on a weekly basis via the CSIRO AWAP website at <<http://www.csiro.au/awap>>.