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The influence of atmosphere-ocean phenomenon on water availability across temperate Australia

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Key Points:

- We investigate the concurrent response of annual rainfall and streamflow to multiple climate variability modes and their interactions
- Climate modes have divergent influences on streamflow and rainfall between and within regions
- In comparison with extreme high rainfall/streamflow, a higher number of extreme low rainfall/streamflow events are related to climate modes

Abstract

Links between climate variability modes, rainfall, and streamflow are important for understanding the trajectories of change and dynamics in water availability. In this paper, we examined the influence of the El Niño Southern Oscillation, Indian Ocean Dipole, Southern Annular Mode, and Interdecadal Pacific Oscillation modes on interannual variations in rainfall and streamflow in four hydroclimate regions. We also explored the link between climate variability modes and extreme rainfall and streamflow years. Climate mode indices, rainfall, and streamflow data from 1975 to 2018 were analyzed for 92 predominately forested catchments located across temperate Australia. Climate modes had divergent influences on streamflow and rainfall between and within regions. Across temperate Australia, a higher proportion of interannual variation in rainfall was explained by climate modes than for streamflow, indicating factors other than atmosphere-ocean phenomena are important in determining interannual streamflow variability. Extremes in rainfall and streamflow across regions were related to the co-occurrence of climate modes, with a stronger relationship between teleconnections and low rainfall/streamflow years than high rainfall/streamflow years. The study provides new insights into the regional drivers of hydrological extremes and consolidates our understanding of the role of teleconnections on water availability in the temperate zone of Australia.

1 Introduction

Temperate regions of Australia are characterized by high interannual and interdecadal rainfall and streamflow variability (Chiew & McMahon, 2002a; Kiem & Verdon-Kidd, 2009; King et al., 2014;

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Potter & Zhang, 2009; Risbey et al., 2009; Zhang et al., 2016) including the occurrence of extreme rainfall events (King et al., 2014; Ummenhofer et al., 2009). This temporal variability of rainfall and streamflow and how it plays out across the continent are strongly affected by climate variability modes, driven by anomalies in Sea Surface Temperature (SST) and their interactions with atmosphere circulations (Biondi et al., 2001; Deser & Phillips, 2009; McBride & Nicholls, 1983; Meneghini et al., 2007; Nicholls, 1989; Power et al., 1999; Saji et al., 1999). Connections between climate anomalies at broad spatial and temporal scales are termed teleconnections (Archer & Fowler, 2004; Cai et al., 2011a). In Australia, the teleconnections are complex and are primarily characterized by the El Niño Southern Oscillation (ENSO) (Chiew & McMahon, 2002a; Hill et al., 2009; McBride & Nicholls, 1983; Verdon et al., 2004), Indian Ocean Dipole (IOD) (Ashok et al., 2003; Cai et al., 2011a; Nicholls, 1989; Raut et al., 2014; Risbey et al., 2009), Southern Annular Mode (SAM) (Feng et al., 2010; Kuhnelt et al., 1990; Meneghini et al., 2007), and the Interdecadal Pacific Oscillation (IPO) (Power et al., 1999; Verdon et al., 2004).

The effects of climate variability modes on rainfall and streamflow vary temporally and spatially (Risbey et al., 2009; Rose et al., 2001). ENSO is the interaction between the atmosphere and the tropical Pacific Ocean; it has three phases: La Niña, El Niño, and neutral (McPhaden et al., 2006; Rasmusson & Wallace, 1983). ENSO influences climate in many parts of the world and is connected to rainfall and streamflow anomalies over northern, eastern, and central parts of Australia, with increased rainfall typically occurring during La Niña phases (Cai et al., 2011a; Chiew & McMahon, 2002a; Chiew et al., 1998; McBride & Nicholls, 1983; Peel et al., 2002; Piechota et al., 1998; Power et al., 1998; Risbey et al., 2009; Verdon et al., 2004). IOD is the interaction between atmosphere circulations and SST in the tropical Indian Ocean (Saji et al., 1999). IOD influences rainfall in Indonesia and eastern Africa (Saji et al., 1999), and is linked to regional rainfall variability over central, southern, and southwest Australia particularly in the June–October period. Typically, more rainfall occurs during the negative IOD phases in Australia (Ashok et al., 2003; Meyers et al., 2007; Risbey et al., 2009; Ummenhofer et al., 2009). SAM is an extratropical phenomenon caused by anomalies of SST and westerly winds around Antarctica (Gong & Wang, 1999). The effects of SAM on Australian rainfall vary depending on the region and season. Declines in rainfall in southwest and southeast Australia during winter and in western Tasmania during summer are linked with a positive SAM. A positive SAM is also associated with the increase in rainfall during summer in the southern east coast of Australia (Ho et al., 2012; Kiem & Verdon-Kidd, 2009; Kuhnelt et al., 1990; Meneghini et al., 2007; Risbey et al., 2009). IPO is the interdecadal interactions between the atmosphere and the tropical Pacific Ocean, and it is linked with decadal climate variability in eastern Australia (Cai & Van Rensch, 2012; Folland et al., 2002; Franks, 2004; Kiem & Franks, 2004; Verdon & Franks, 2006), with more rainfall occurring during negative IPO phase (Henley & King, 2017; Henley et al., 2015; Power et al., 1999; Verdon et al., 2004). The cycles of the IPO are closely related to the Pacific Decadal Oscillation (PDO), with the latter representing the North Pacific (Folland et al., 2002; Mantua et al., 1997) and the former the whole Pacific basin (Power et al., 1999). Climate variability modes interact together; forming complex climate systems due to their simultaneous atmospheric and oceanic oscillations (Behera et al., 2006; Wise et al., 2015; Yu et al., 2015; Yuan & Li, 2008). The interactions between climate modes have been found for ENSO and IOD (Behera et al., 2006; Cai et al., 2011a; Meyers et al., 2007; Risbey et al., 2009), ENSO and IPO (Cai & Van Rensch, 2012; Kiem et al., 2003; Risbey et al., 2009; Verdon et al., 2004), and ENSO and SAM (Pohl et al., 2010).

In the temperate zone of Australia, there is evidence that climate change is influencing spatial and temporal patterns of rainfall and streamflow, although the effects of climate change vary between regions and are difficult to ascertain due to high interannual variability (Head et al., 2014; Nicholls & Collins, 2006). Further impacts are predicted under future climate change (Chiew & McMahon, 2002b; Petrone et al., 2010; Silberstein et al., 2012). Although climate change significantly affects streamflow, these effects are not linear with the changes in rainfall, nor are they spatially uniform (Saft et al., 2015; Saft et al., 2016; Silberstein et al., 2012). Changes in rainfall/runoff coefficient and shifts in streamflow after long-term droughts suggest that variable hydrologic responses are at work, influencing both annual streamflow and post-drought recovery times (Petrone et al., 2010; Saft et al., 2016). Studies have found a non-linear decrease in streamflow/rainfall ratios, with some catchments exhibiting no recovery of streamflow following the end of the Millennium Drought (2001-2009) in southeastern Australia (Saft et al., 2015; Saft et al., 2016).

To understand the implications of a changing climate and climate variability (i.e., cycles of wet and dry periods) on water availability and extreme hydrological events we need to understand how atmosphere-ocean processes have shaped the observed variability of rainfall and streamflow. Existing studies have identified some key links between water availability and climate variability modes for Australia. For example, Hendon et al. (2007) showed that in the southeast, southwest, southern east coast of Australia and western Tasmania, SAM accounts for 15% of the weekly variance in winter rainfall. Risbey et al. (2009) found that ENSO explains up to 25% to 50% of rainfall variance, depending on the season and region in Australia. Van Dijk et al. (2013) found that three to four climate phenomena explained 53% to 73% of the variance in 5-year rolling average patterns of precipitation across Australia. Piechota et al. (1998) suggested that in southeast Australia, ENSO can be used to help forecast spring runoff and for the east coast and northeast Australia summer runoff. Kiem and Verdon (2009) found that ENSO alone accounts for a small proportion of streamflow variability in Victoria. Verdon et al. (2004) found a strong relationship between seasonal streamflow and ENSO and IPO in New South Wales (NSW), Queensland (QLD), and Victoria (VIC). They showed that streamflow during the La Nina phase in NSW and QLD increased significantly while La Nina effects declined southward towards VIC. The study also found that wetter conditions during La Nina events occurred when the IPO was in the negative phase.

The above referenced studies have produced important knowledge of these crucially important hydrologic questions. However, there are difficulties in obtaining a consolidated understanding of the climate mode-hydrology interactions for four reasons. The first is that the existing studies have used a range of methodologies and data records, including a number of studies that focused on either rainfall or streamflow but not both, and the inconsistent use of climate modes. Secondly, there is variable regionalization, which is often somewhat arbitrary with respect to climate phenomenon and ecohydrology. Third, the majority of studies are correlative rather than predictive. Fourth, few studies explored the role of climate modes on both means and extremes in rainfall or streamflow. The varying approaches make it difficult to understand the implications for streamflow and water availability in temperate forests when considered alongside climate change and ecohydrological factors such as wildfire and dynamic runoff ratios.

In this paper we provide consolidated analysis of teleconnections and hydrology across the temperate forests of Australia with an emphasis on the following key aspects that are important to our understanding effects of teleconnections in the context of a changing climate and other sources of streamflow variability:

- Predictability - we develop and test models, rather than correlative interactions;
- Regionalization – we constrain the analysis to the temperate forests of Australia and structure our study around natural resource management (NRM) regions, which are meaningful in the context of climate change and climate drivers; and,
- we address the influence of climate modes on both means and extremes in rainfall and streamflow - both measures of change are important and may have different levels of connection with regional climate drivers

To address these constraints, and to provide a consolidated analysis of teleconnections and their implications for water availability in temperate forests of Australia (Figure 1), this study investigated the concurrent response of annual rainfall and streamflow to multiple climate modes and their interactions. To account for non-symmetry in extreme hydroclimate conditions and their links to climate modes we specifically analyzed the relationship between dry/wet extremes and concurrent climate modes. The paper aimed to answer the following questions:

1. How do hydroclimate regions of temperate Australia compare in terms of interannual rainfall and streamflow variability?
2. What is the multivariate influence of ENSO, IOD, SAM, and IPO on annual rainfall and streamflow, and do their responses vary?
3. What are the relationships between hydrological extremes and concurrent phases of climate modes?

2 Methods

2.1 Study area

The study design was structured around two climate classification schemes; the Koppen-Geiger climate classification (Peel et al., 2007), which was used to define the Australian temperate zone (Figure 1a), and the Natural Resources Management (NRM) classification system (NRM regions, 2020) which was used to assign study catchments to different geographic regions within the Australian temperate zone (Figure 1b). The NRM classification system clusters catchments and regions based on broad-scale climate and biophysical factors and based on their potential vulnerability to the impact of climate change (NRM regions, 2020). There are five NRM clusters within the temperate zone: Southern Slopes (SS), Murray Basin (MB), East Coast (ES), Central Slopes (CS), and Southern and Southern West Flatlands (SSWF) (Figure 1c).

Catchments in these regions are typically dominated by native Eucalyptus forests. Forest types range from open woodland to tall wet forests. The terrain is highly variable with some areas within the Great Dividing Range located along the east coast having headwaters in steep dissected uplands. In other areas, such as western Victoria and the southern parts of western Australia, the catchments are in less rugged terrain. Mean annual rainfall and seasonality is also highly variable. In the south of western Australia, the mean annual rainfall is 694 mm/year with most falling in winter (Charles et al., 2010), while in southeast Australia mean annual rainfall across the study area is 953 mm/year. Rainfall also varies at a local scale. For example, the western part of Tasmania is mountainous and subjected to orographic rainfall while the east part is flat. The

Spatially interpolated rainfall data from 1975 to 2018 were collated for each catchment. Catchments were first delineated from the Shuttle Radar Topography Mission (SRTM) digital elevation model dataset with a cell size of 0.00416 degrees (USGS, 2019). Rainfall data for each catchment was then extracted from the gridded rainfall dataset that forms part of the Australian Water Resource Assessment Landscape (AWRA-L) project. These interpolated grids are produced for the Australian continent based on rainfall data from 6500 rainfall gauge stations and interpolated to a 0.05 degree (approximately 5×5 km) (Frost et al., 2016). The accuracy of daily rainfall in these grids, described in (Beesley et al., 2009) is estimated to be in the order of 0.01 mm, 0.85 mm, and 3.43 mm for mean error, mean absolute error, and root mean square error, respectively. Since interannual variability in rainfall is a critical part of our study we compared the range of coefficient of variation of annual rainfall from the interpolated rainfall dataset with 50 gauged rainfall stations across temperate Australia to test the robustness of the interpolated data. Potential Evapotranspiration (PET) in AWRA-L is calculated on a 0.05 degree national grid using the Penman equation (Penman, 1948). The daily gridded minimum and maximum temperature, downward solar irradiance, and wind speed at 2 m were used to produce the PET dataset (McVicar et al., 2008).

Historical records of indices of climate variability modes were derived from available online data. NINO 3.4, Dipole Mode Index (DMI), and Tripole Index (TPI) for the Interdecadal Pacific Oscillation were downloaded from the Global Climate Observing System (GCOS) Working Group on Surface Pressure (WG- SP) (WGSP, 2019). The SAM history index was downloaded from the Climate Data Guide dataset (Climate Data Guide, 2019). NINO 3.4 is an index used to measure the development and intensity of ENSO. It is the area-averaged SST from 5S-5N and 170-120W calculated from the HadISST1 (Rayner et al., 2003). DMI is used to measure the IOD. It is the anomalous Sea Surface Temperature (SST) gradient between the western (50E-70E and 10S-10N) and the southeastern (90E-110E and 10S-0N) equatorial Indian Ocean (Saji & Yamagata, 2003). SAM index is the difference of zonal mean sea level pressure between 40°s and 65°S (Marshall, 2003). TPI is an index to measure IPO. It is based on the difference between the SSTA (Sea Surface Temperature Anomaly) averaged over the central equatorial Pacific and the average of the SSTA in the Northwest and Southwest Pacific (Henley et al., 2015). There are other indices used to measure IPO (e.g. Cai & Whetton, 2001; Folland et al., 1999; Folland et al., 2002; Mantua et al., 1997; Parker et al., 2007; Power et al., 1999). The UKMO IPO index (Folland et al., 1999; Folland et al., 2002) is a commonly used IPO index used to define the relationship between Australian rainfall/streamflow with IPO. The TPI represents the IPO phenomenon in a more stable and robust manner than the UKMO IPO index, and it is explicitly aligned with the observed spatial pattern of the IPO (Henley et al., 2015; Henley et al., 2017). There is however a strong correlation between TPI and the UK Met Office IPO index (Henley et al., 2015). The correlation between two indexes ranges from 0.92 to 0.97 for different datasets of TPI and UK Met Office IPO. For filtered datasets, the correlations range from 0.85 to 0.97 (Henley et al., 2015). Further information about TPI and IPO indices and their differences is provided in Henley et al (2015).

The length of the collected dataset was defined based on the availability and quality of streamflow data. To capture the historical trends and variability of IPO, which is an interdecadal climate variability mode, a number of catchments with longer records of streamflow data are required. Unfortunately, across our study region, the amount of data on streamflow extending before 1975 decreased with increasing time such that among the selected catchments only 4 catchments had 68 years of streamflow data (68 is the maximum length), and 19 catchments (5 in SS, 6 in MB, 3 in

SSWF, and 5 in EC+CS) had streamflow data ≤ 68 and ≥ 60 years. These nineteen catchments do not provide a sufficient sample size nor a representative sample of the spatial coverage of hydroclimate regions in the Australian temperate zone for a robust analysis. Furthermore, catchments with a longer duration of data are subject to data quality issues. To address potential biases that may have influenced our data from 1975 onwards we compared the statistical distribution and standard deviation of the TPI data from 1975 to 2018 with the data from 1900 to 1975 and data from 1900 to 2018. The statistical distribution and standard deviation for all climate mode indices for these three periods were approximately equal. The standard deviation for IPO time series data from 1976-2018 was 0.60 and for IPO data from 1900 to 1975 and from 1900 to 2018 was 0.64 and 0.62, respectively.

2.3 Analyses

2.3.1 Variation and trend in annual rainfall and streamflow

To understand how annual rainfall and streamflow varied between and among catchments in each region we analyzed the coefficient of variation (CV), standard deviation, and mean of the interannual variability of rainfall and streamflow for each catchment using data between 1975 to 2018. These were summarized according to hydroclimate regions. The relationship between changes in the range of CV of streamflow among catchments from one region to another and hydroclimate factors (mean annual rainfall and PET) in those regions were analyzed to understand how the range of CV of streamflow in each region is related to mean annual rainfall and PET.

Precipitation patterns have changed across temperate Australia since records began due to changes in climate (Bureau of Meteorology, 2021a). To account for the possible bias imparted into our analysis by continued climate forcing on precipitation and streamflow patterns we undertook a trend analysis of annual rainfall and streamflow between 1975 to 2018 for each region. For this analysis, we used the Mann-Kendall (MK) trend test (Hamed, 2008; Hamed & Rao, 1998). We used the Hamed and Rao Modified MK Test which uses a variance correction method to improve trend analysis and consider serial autocorrelations (Hamed & Rao, 1998). The significance level in our analysis was 0.05. For more information about the MK trend test see Supplement text S1.

2.3.2 Effects of climate modes on rainfall and streamflow

Random forest machine learning models were used to investigate the combined effects of climate modes (ENSO, IOD, SAM, and IPO) on rainfall and streamflow in each hydroclimate region (SS, MB, EC+CS, and SSWF). Random forest is a bagging ensemble learning method that can consider complex interactions between variables and constructs multiple classifiers or regressors trees and aggregates their results (Breiman, 2001, 2002). Recent studies have shown that random forest is a robust modeling approach for predicting water resources in comparison with other models such as support vector regression, artificial neural networks, and linear models (Li et al., 2016; Tyralis et al., 2019). For more information on random forest models see Supplement text S2.

The association between annual rainfall and streamflow with climate modes in each region was modeled in two steps. In the first step, data were split into a train set and test set. We allocated 80% of the data to the train set and 20% to the test set. The random forest model was trained using train set data. In step two, the model was evaluated using the test set, and the Explained Variance

(EV) and Feature Importance (FI) metrics were calculated for each region. The importance of each variable in the random forest model is estimated by defining how much the error in prediction increases when data for that variable is changed while other variables are held constant (Breiman, 2002; Liaw & Wiener, 2002).

2.3.3 Concurrent effects of climate modes on hydrological extremes

Hydrological extremes were examined in relation to the two most influential climate modes in each region. The two climate modes with the highest association were determined by the outputs from our statistical analysis. The number of years with extremely low or high annual rainfall and streamflow during concurrent phases of climate modes was determined for catchments in each region. Extreme rainfall years were defined based on the definition by BoM for rainfall percentiles. According to BoM, 10th percentiles of a time series of rainfall are designated as extreme low rainfall and 90th percentiles as extreme high rainfall (Bureau of Meteorology, 2019d). The probability of extreme low annual rainfall years for each concurrent phase of climate modes was then calculated by dividing the number of years with extreme low annual rainfall during that concurrent phase by the total number of years with extreme low rainfall. The relationship between hydrological extremes with concurrent phases of climate modes was tested using a contingency table and the chi-square test. Probability density functions for each of the climate modes were calculated to quantify the relationship between the extreme events across the range of each climate mode index. The same analysis was performed for streamflow extremes.

3 Results

3.1 Variation and trend of annual rainfall and streamflow

The CV in annual streamflow was higher than the CV in annual rainfall for each region (Figure 2a). The increased CV in streamflow was due to the higher standard deviation in annual streamflow compared to rainfall (Figure 2b) relative to the mean values of annual rainfall and streamflow (Figure 2c). The range of the CV provided a standardized metric that allows for comparisons in interannual variability of streamflow and rainfall to be made within and between regions. Figures S1 (SS), S2 (MB), S3 (EC+CS), and S4 (SSWF) in the supplementary material provide additional information about the CV of streamflow and rainfall among catchments in each region. Our analysis of the range of the CV of gauged rainfall stations for 50 catchments showed that the range of the CV of rainfall was between 0.12 and 0.3 (Figure S9 in the supplementary material) which was consistent with our analysis based on interpolated rainfall data.

The range of interannual variability in streamflow among catchments in MB was larger than in other regions. In the EC+CS, the range of the variation in annual streamflow was smaller than in other regions but most of the catchments in this region had a high CV in streamflow. The difference in the variation range of streamflow and rainfall also varied from region to region. This difference in the ranges was greater in SSWF than in other regions. Analysis of the relationship between the CV of streamflow and hydroclimate factors showed that with increasing mean annual rainfall (Figure S5) (which corresponded to decreasing mean annual PET (Figure S6)) and mean annual streamflow (Figure S7), the CV of streamflow decreased. With decreasing mean annual rainfall and annual streamflow, the CV of streamflow increased. With an increasing CV of rainfall, the

streamflow to climate modes in comparison with the rainfall. Our analysis with the paired data on rainfall and streamflow show that ENSO has a higher association with rainfall than streamflow. Although the association between IOD with rainfall is higher than ENSO in the SS and MB, and IPO in the EC+CS. In all regions, except EC+CS for IOD, the relative influence of IOD and SAM on streamflow is higher than rainfall. This is consistent with previous studies. For example, Kiem and Verdon (2009) found that ENSO accounted for a smaller proportion of streamflow variability in Victoria, while many studies have found a strong relationship between rainfall and ENSO in this region (e.g. Ashcroft et al., 2016; Cai et al., 2011a; Chiew et al., 1998; Ropelewski & Halpert, 1987). Moreover, teleconnections accounted for a much lower proportion of the variation of streamflow (Figure 5) compared to rainfall (Figure 4). This may be because of the lag effects on streamflow. We repeated the analysis for one, two, and three months of lag streamflow, but the results remained similar. More information about the influence of teleconnections and lag effects of streamflow is provided in the supplementary material (Figures S12, S13, and S14). Another factor driving streamflow variability may be rainfall distributions within years (Dettinger & Diaz, 2000; Fiddes & Timbal, 2016), which can have large impacts on the conversion of rainfall to streamflow at annual timescales. These divergent responses of streamflow and rainfall to climate modes are important for making predictions of streamflow response to climate variability modes.

When interpreted in the context of the overall patterns of interannual variability in rainfall and streamflow (Figure 2), our analysis of rainfall, streamflow, and links to teleconnections suggests that catchment properties that modulate the water balance are a key consideration for predicting the streamflow response to dynamics hydroclimatic conditions. The strength of local controls on interannual variability depending on region, as indicated by patterns in the interannual CV of rainfall and streamflow (Figure 2). The temporal CV of rainfall remains fairly homogenous through the temperate zone, while temporal CV in streamflow shows distinct differences from one region to another. These results suggest that finer-scale factors, other than rainfall and climate drivers, are likely having a large impact on the temporal (inter-annual variability) in streamflow. These processes will likely operate in different ways depending on geographic context and associated ecohydrological processes. Changes to vegetation, either through land-use (Liu et al., 2019; Webb & Jarrett, 2013) or wildfires (Feikema et al., 2013; Nolan et al., 2015), or prolonged droughts are all possible factors at play, as are the dynamics of catchment storage and groundwater-surface water hydraulic connections (Chiew et al., 2014; Potter et al., 2005). The role of Evapotranspiration (ET), as the largest term in the water balance, is of particular importance. This is supported by our analysis (in supplementary Figures S5-S8) which showed a relationship between streamflow variability and hydroclimate factors such as mean annual rainfall and PET.

Consistent with earlier studies, our analysis shows that more arid landscapes are more variable (both rainfall and streamflow) from one year to the next. For rainfall, this variability is primarily a function of climate and weather, although possible feedbacks with land-use and ecohydrology have been proposed (Andrich & Imberger, 2013; Junkermann et al., 2009). For streamflow, with a much higher interannual variability, this variation is a function of the rainfall but more importantly the catchment processes that govern the water balance (Jothityangkoon et al., 2001; Ning et al., 2017; Tian et al., 2017). These processes, particularly water use by trees, are likely to drive variability up in drier areas more than they do in wet areas where ET is less dependent on rainfall (Deb et al., 2019; Moreno et al., 2012). Interestingly, the streamflow in more arid regions (MB and SSWF) also appears to be more responsive to non-stationary climate, with both showing significant decreasing trends in streamflow. While this decreasing trend in streamflow has been

documented previously (Petroni et al., 2010; Silberstein et al., 2012; Zhang et al., 2016) our results pointing towards this trend being stronger in drier climates is a novel finding.

Given the importance of climate modes on the temporal patterns in streamflow and rainfall variability, our ability to predict future changes in these is contingent on our understanding of how sea surface temperature (SST) and large-scale weather phenomena play out under increased temperatures as predicted with climate change. Research indicates an intensification in ENSO (Cai et al., 2018; Cai et al., 2015; Kim et al., 2014) which means increased rainfall variability. Although the ability to simulate climate modes has improved in current climate models (e.g. from CMIP5 to CMIP6) (Fasullo et al., 2020; Grose et al., 2020; Jiang et al., 2021), simulating and representing these key drivers of change in rainfall at a finer spatial scale is still a challenge for these models (Chen & Jin, 2021; Liao et al., 2021). By linking our predictive models to these future climate mode scenarios there is an opportunity to explore how future variability in climate modes may influence rainfall and streamflow across Australian temperate forests without having to resort to physical modeling to simulate catchment streamflow. However, for streamflow, where climate modes and rainfall variability explain a lower proportion of the variability, understanding how changes in vegetation, soil, and water use by vegetation influence streamflow variability are of critical importance. Incorporating ecohydrological dynamics into streamflow predictions is therefore critical for understanding future change. For example, wildfires have burnt millions of ha. in the regions studied in this paper (Cameron et al., 2009; Filkov et al., 2020; McCarthy et al., 2012). While responses may vary according to burn severity, species, and post-fire rainfall, a common response is reduced evapotranspiration, which ameliorates the effect of lower rainfall (Lane et al., 2006; Lane et al., 2010; Nolan et al., 2015). There are also hypotheses about hydraulic disconnection (groundwater disconnecting with streams) following long dry periods that could result in long-lasting changes to rainfall-runoff relationships (Hughes et al., 2012; Kinal & Stoneman, 2012). Both of these examples would disconnect, to a greater or lesser degree, rainfall and streamflow relationships and therefore the teleconnections with climate modes. However, in the development of ecohydrological models for streamflow prediction, there is a strong need to seek alignment between mechanisms of hydrological change and the regional hydroclimate drivers such as climate mode variability, which influence rainfall (both the amounts and variability) and which are directly impacted by global warming (Cai et al., 2015; Chiew & McMahon, 2002b; Delage & Power, 2020; Kim et al., 2014; Silberstein et al., 2012).

5 Conclusions

Australian temperate zones are characterized by high variability of interannual rainfall, streamflow, and occurrence of hydrological extremes. Climate variability modes are important factors simultaneously influencing the high variability of interannual rainfall and streamflow in biophysical regions of the Australian temperate zone. Hydrological extremes of low annual rainfall and streamflow years are strongly correlated with the effects of co-occurrence phases of regional climate modes. These years with extreme low rainfall and streamflow can be most problematic due to a shortage of water for domestic, agriculture, and increasing the risk of more droughts and wildfires.

Despite the consistent response for rainfall across the region, the interannual variation of streamflow in catchments was higher than rainfall. This result was also consistent across the region suggesting that while rainfall is an important broad-scale driver of streamflow other factors are at

play. We hypothesize that catchment soil and vegetation properties and disturbance history may be influencing the streamflow variability at finer scales. This has implications for predicting future streamflow as changes in rainfall to future climate change may not scale linearly to change in streamflow; however, the quantified teleconnections between climate modes and rainfall and streamflow provide a broad scale tool for understanding changes in water resource availability across temperate Australia.

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Tables

Table 1. Mean area, forested area, elevation, and mean annual rainfall, streamflow, and PET in each hydroclimate region. The table also shows the min-max range of these factors among catchments in each region.

		SS	MB	EC+CS	SSWF
Number of catchments		22	46	15	9
Area (km ²)	Min – Max	91 - 1113	81 - 4740	101 - 2530	74 - 1525
	Mean	421	463	484	478
Elevation (m)	Min range	16 - 936	115 - 982	79 - 908	20 - 217
	Max range	420 - 1859	295 - 1983	975 - 1507	160 - 570
	Mean	678	634	744	262
Annual precipitation (mm)	Min range	367 - 1886	188 - 861	335 - 738	282 - 703
	Max range	1166 - 3280	786 - 2037	857 - 1415	1011 - 2416
	Mean	1297	935	869	1010
Annual streamflow (mm)	Min range	2 - 2633	0 -121	0 - 64	1 - 32
	Max range	181 - 2634	85 - 796	18.5 - 497	178 - 973
	Mean	592	165	85	144
Annual PET (mm)	Min range	666 - 982	842 - 1144	1018 - 1263	1062 - 1356
	Max range	1080 - 1465	1331 - 1730	1577 - 1927	1563 - 1972
	Mean	1211	1404	1655	1614
Forested area (%)	Min – Max	15 – 99	2 - 100	10 – 80	64 - 100
	Mean	76	60	47	91

Table 2. The probability of the extreme low and high rainfall events during concurrent phases of the two most important climate modes in each hydroclimate region. Colored cells show the concurrent phases of climate modes with the highest probabilities of low and high extreme rainfall years for each region.

Region	Concurrent phases of climate variability modes	Total number of extreme low/high rainfall events	Number of extreme low rainfall events during each concurrent phase	Probability of extreme low rainfall events during the concurrent phase	Number of extreme high rainfall events during concurrent phases	probability of extreme high rainfall events during the concurrent phase	P-value (Chi-square test)
SS	El Nino - pIOD	110	90	0.82	28	0.25	0.0
	El Nino - nIOD		2	0.02	11	0.1	
	La Nina - nIOD		4	0.04	39	0.35	
	La Nina - pIOD		14	0.12	32	0.3	
MB	El Nino - pIOD	230	221	0.96	67	0.29	0.0
	El Nino - nIOD		1	0.004	43	0.19	
	La Nina - nIOD		0	0.0	55	0.24	
	La Nina - pIOD		8	0.036	65	0.28	
EC+CS	El Nino - pIPO	75	69	0.92	16	0.21	0.0
	El Nino - nIPO		0	0	5	0.06	
	La Nina - nIPO		6	0.08	54	0.73	
	La Nina - pIPO		0	0	0	0	
SSWF	El Nino - pIOD	45	30	0.66	13	0.29	0.0
	El Nino - nIOD		0	0	6	0.13	
	La Nina - nIOD		0	0	11	0.24	
	La Nina - pIOD		15	0.34	15	0.34	

Table 3. The probability of the extreme low and high streamflow events during concurrent phases of the two most important climate modes in each hydroclimate region. Colored cells show the concurrent phases of climate modes with the highest probabilities of low and high extreme streamflow years for each region.

Region	Concurrent phases of climate variability modes	Total number of extreme low/high streamflow events	Number of extreme low streamflow events during each concurrent phase	Probability of extreme low streamflow events during the concurrent phase	Number of extreme high streamflow events during concurrent phases	probability of extreme high streamflow events during the concurrent phase	P-value (Chi-square test)
SS	pSAM - pIOD	110	91	0.83	28	0.25	0.0
	pSAM - nIOD		8	0.07	20	0.18	
	nSAM - nIOD		4	0.04	47	0.43	
	nSAM - pIOD		7	0.06	15	0.13	
MB	pSAM - pIOD	230	175	0.76	77	0.33	0.0
	pSAM - nIOD		5	0.02	23	0.1	
	nSAM - nIOD		7	0.03	117	0.51	
	nSAM - pIOD		43	0.19	13	0.06	
EC+CS	El Nino - pIPO	75	65	0.87	7	0.09	0.0
	El Nino - nIPO		4	0.05	8	0.11	
	La Nina - nIPO		6	0.08	60	0.80	
	La Nina - pIPO		0	0.0	0	0.0	
SSWF	pSAM - pIOD	45	40	0.89	10	0.22	0.0
	pSAM - nIOD		0	0	7	0.16	
	nSAM - nIOD		0	0	17	0.38	
	nSAM - pIOD		5	0.11	11	0.24	

Figures captions

Figure 1. Koppen-Geiger climate classification defines the Australian temperate zone (a) and NRM clusters define the biophysical regions of Australia based on their potential variability to climate change (b). Selected catchments in biophysical regions of the Australian temperate zone (c).

Figure 2. Range of the coefficient of variations (a), standard deviations (b), and means (c) of the interannual variability in rainfall and streamflow in each region. The range of the CV shows the relative differences between interannual variability of streamflow and rainfall in each region and among regions.

Figure 3. The Mann-Kendall trend test analysis for streamflow and rainfall data from 1975 to 2018 shows no change in the trend of rainfall and streamflow in the SS (a) and EC+CS (c). Streamflow in the MB (b) and SSWF (d) has decreased, and in MB the trend of rainfall remained constant. In the SSWF there is a decrease in the trend of rainfall, but it is not statistically significant.

Figure 4. Explained variance and the relative importance of climate modes on the variation of rainfall in the SS (a), MB (b), CS+EC (c), and SSWF (d).

Figure 5. Explained variance and the relative importance of climate modes on the variation of streamflow in the SS (a), MB (b), CS+EC (c), and SSWF (d).

Figure 6. Distribution of extreme low and high annual rainfall years during concurrent phases of two most important climate modes in the SS (a), MB (b), EC+CS (c), and SSWF (d). The size of the circles shows the percentage of the catchments in each region which experienced extreme rainfall during concurrent phases of climate modes. The larger the size of the circle, the higher number of catchments that experienced extreme rainfall during concurrent phases of climate modes. For each graph, the probability density of x-axes is shown on top, and the probability density of y-axes is shown on the rights side of the graph.

Figure 7. Distribution of extreme low and high annual streamflow years during concurrent phases of two most important climate modes in the SS (a), MB (b), EC+CS (c), and SSWF (d). The size of the circles shows the percentage of the catchments in each region which experienced extreme streamflow during concurrent phases of climate modes. The larger the size of the circle, the higher number of catchments that experienced extreme streamflow during concurrent phases of climate modes. For each graph, the probability density of x-axes is shown on top, and the probability density of y-axes is shown on the rights side of the graph.













