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Copula-statistical precipitation forecasting model in Australia's agro-ecological zones

Thong Nguyen-Huy[a,b,d], Ravinesh C. Deo[a,b,d,*], Duc-Anh An-Vo[b,c,d], Shahbaz Mushtaq[b,d], Shahjahan Khan[a,b,d]

[a] School of Agricultural, Computational and Environmental Sciences, QLD 4300, Australia
[b] International Centre for Applied Climate Sciences (ICACS), QLD 4300, Australia
[c] Computational Engineering and Science Research Centre (CESRC), QLD 4300, Australia
[d] University of Southern Queensland, Institute of Agriculture and Environment (IAg&E), QLD 4300, Australia

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ABSTRACT

Vine copulas are employed to explore the influence of multi-synoptic-scale climate drivers – El Niño Southern Oscillation (ENSO) and Inter-decadal Pacific Oscillation (IPO) Tripole Index (TPI) – on spring precipitation forecasting at Agro-ecological Zones (AEZs) of the Australia's wheat belt. To forecast spring precipitation, significant seasonal lagged correlation of ENSO and TPI with precipitation anomalies in AEZs using data from Australian Water Availability Project (1900–2013) was established. Most of the AEZs exhibit statistically significant dependence of precipitation and climate indices, except for the western AEZs. Bivariate and trivariate copula models were applied to capture single (ENSO) and dual predictor (ENSO & TPI) influence, respectively, on seasonal forecasting. To perform a comprehensive evaluation of the developed copula-statistical models, a total of ten *one*- and *two*-parameter bivariate copulas ranging from elliptical to Archimedean families were examined. Stronger upper tail dependence is visible in the bivariate model, suggesting that the influence of ENSO on precipitation forecasting during a La Niña event is more evident than during an El Niño event. In general, while the inclusion of TPI as a synoptic-scale driver into the models leads to a notable reduction in the mean simulated precipitation, it depicts a general improvement in the median values. The forecasting results showed that the trivariate forecasting model can yield a better accuracy than the bivariate model for the east and southeast AEZs. The trivariate forecasting model was found to improve the forecasting during the La Niña and negative TPI. This study ascertains the success of copula-statistical models for investigating the joint behaviour of seasonal precipitation modelled with multiple climate indices. The forecasting information and respective models have significant implications for water resources and crop health management including better ways to adapt and implement viable agricultural solutions in the face of climatic challenges in major agricultural hubs, such as Australia's wheat belt.

1. Introduction

Australia, an agricultural nation, has a relatively high inter-annual variability in climatic properties (including annual and seasonal precipitation); which is about 15–18% higher than any other major agricultural nation (Best et al., 2007; Cleugh et al., 2011; Mekanik and Imteaz, 2013; Walker and Mason, 2015). The Australian precipitation is influenced by the synoptic-scale processes mainly of tropical oceanic and atmospheric origin, with the primary attention largely paid to the different phase of the El Nino Southern Oscillation (ENSO) (Risbey et al., 2009; Schepen et al., 2012). An association between ENSO and the precipitation have been investigated since the early '80s (McBride and Nicholls, 1983), which ENSO phenomenon producing a strong impact on seasonal precipitation from July–March. The magnitude and timing of the effect varies considerably with the sites and coincides with major cropping periods (McBride and Nicholls, 1983; Stone et al., 1996). Interdecadal Pacific Oscillation (IPO) is also associated with climate variations across the Pacific, albeit on decadal timescales, acting to modulate the interannual variation of ENSO-related effects (Salinger et al., 2001), and is directly attributable to the shift in the intertropical convergence zone (Folland et al., 2002). However,

* Corresponding author at: School of Agricultural, Computational and Environmental Sciences, QLD 4300, Australia.
E-mail addresses: ThongHuy.Nguyen@usq.edu.au (T. Nguyen-Huy), ravinesh.deo@usq.edu.au, physrcd@yahoo.com (R.C. Deo).

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Southern Oscillation Index (SOI) features in Australia are reinforced in negative IPO phases in some areas, with lesser impacts in others (Chiew and Leahy, 2003). Also, individual ENSO events have stronger and more predictable impacts across Australia during the negative (cool) IPO phases (Kirono et al., 2010). Power et al. (1999) found no significant relationship between interannual climate variability and ENSO in the positive IPO phases, although a relationship between IPO and precipitation, river flow and wheat yield, were identified in negative phases. While a better understanding of ENSO's impact in different IPO phases is creating an opportunity for improving the performance of forecasting model, the mechanism of interdecadal modulation of IPO on ENSO-related climatology, including precipitation, is complicated. Precipitation forecasting, however, is an important task for agricultural water management and agricultural economics (An-Vo et al., 2015; Deo et al., 2017), affecting subsistence and commercial aspects of Australia's agricultural industry (Anwar et al., 2007; Best et al., 2007; Chiew et al., 2003; Montazerolghaem et al., 2016).

In published literature, Risbey et al. (2009) has identified the key rivers of Australian precipitation variability based on concurrent relationships between synoptic-scale climate indices and precipitation. However, to forecast future precipitation, lagged relationships between climate indices in the current and the (next) seasonal precipitation are important. Further, a strong concurrent relationship does not always lead to a strong lagged relationship (Schepen et al., 2012). Although such lagged relationships have been widely applied to forecast the precipitation in Australia, the authors utilised either a single climate index (Chiew et al., 1998; Stone et al., 1996; Taschetto and England, 2009) or assessed the impact of each climate index separately (Hasan and Dunn, 2012; Kirono et al., 2010; Schepen et al., 2012). In general, the influence of different climate indices varies across seasons and regions. For example, in north-eastern Australia, spring precipitation was found to exhibit the highest correlation with Niño-4.0 and thermocline properties, while optimal predictors for summer precipitation were Niño-4.0 and Dipole Mode Index (Kirono et al., 2010). Such temporal and spatial variations of the impact of different climatic indices have been also confirmed in an extensive research by Schepen et al. (2012). However, in spite of an acceptable level of model performance for seasonal forecasting, utilisation of a single predictor can hinder forecasting ability since relationships between climate indices and precipitation can be relatively complex (Rasel et al., 2016; Wang and Hendon, 2007).

In Australia, the impacts of different climate indices on precipitation amounts vary according to the continent's geographic diversity (Chowdhury and Beecham, 2010; Deo et al., 2017). In spite of this, only a handful of research has considered the joint influence of multiple indices on seasonal precipitation forecasting. Mekanik and Imteaz (2013) combined ENSO and Indian Ocean Dipole to develop a model for spring precipitation in south-eastern Australia. Rasel et al. (2016) incorporated SOI and Southern Annular Mode to demonstrate 63% better prediction accuracy of spring precipitation in South Australia compared to a single index. However, these studies employed a regression model where the dependence structure between an index and precipitation was measured by Pearson's correlation, whilst assuming linearity and normal distributions. Precipitation data, however, exhibits a skewed distribution and its relationship with climate indices is nonlinear (Schepen et al., 2012) which invalidates the use of Pearson's correlation and normal assumption. As the dependence structure between the predictors of precipitation and the predictand (i.e., precipitation) is governed by the marginal distributions of these variables that can help decision-makers to capture the 'cause and effect' relationships,, a robust forecasting model must allow the establishment of the linear or nonlinear dependence between the predictors (*e.g.*, climate indices) and predictand (*e.g.*, precipitation) with the marginal distributions being derived from diverse distribution families. Here, we aim to achieve such a novel forecasting method by employing copula-statistical models, which are yet to be applied for precipitation forecasting research in the present study region.

Copula-statistical models (Sklar, 1996; Sklar, 1959) that utilise ranked Spearman or Kendall tau coefficients provide viable alternatives for modelling non-linear dependences, and have attracted much attention in bivariate and trivariate based modelling (De Michele and Salvadori, 2003; Evin and Favre, 2008; Hao and Singh, 2016; Rauf and Zeephongsekul, 2014; Zhang and Singh, 2007). Copula functions allow to model the dependence structure independently from the marginal selection. Further, they overcome issues associated with joint dependences between rare events (*e.g.*, precipitation extremes) by considering tail dependences (*i.e.*, asymmetric dependence structure) which is impossible with simplistic statistical models. Since their advent, recent years have witnessed an extensive application of copulas for: insurance and financial risk (Fang and Madsen, 2013; Jaworski et al., 2013; Trede and Savu, 2013), hydrology and water resources (Favre et al., 2004; Hao and Singh, 2013; Wong, 2013), drought (Wong et al., 2010; Wong et al., 2013; Yang, 2010), flood (Chowdhary et al., 2011; Favre et al., 2004) and streamflow (Hao and Singh, 2012; Lee and Salas, 2011). Khedun et al. (2014) applied multivariate Gaussian and Archimedean copulas for modelling the effect of ENSO and PDO on precipitation anomalies in Texas. However, multivariate Gaussian copulas, as applied in that study, can have a drawback by restricting the symmetric dependence associated with elliptical copulas. Also, multivariate Archimedean copulas employ a single parameter on pairs of variables which assumes the same dependence structure for variable pairs. Such an assumption might be unrealistic (Hao and Singh, 2016). In addition, to the best of our knowledge, copula-statistical models have not been explored for probabilistic forecasting of seasonal precipitation in Australia, despite that the challenges and a need for a robust model for spring precipitation forecasting at Agro-ecological Zones (AEZs) of the Australia's wheat belt.

In this paper, we model the joint influence of ENSO (through the phases of the Southern Oscillation Index, SOI) and IPO Tripole Index (TPI) on seasonal precipitation at the AEZs using vine copulas. The TPI (which is a robust and stable representation of the IPO with less variance in the decadal than the shorter timescales compared to Niño 3.4 due to an inclusion of off-equatorial sea surface temperature (SST)) (Henley et al., 2015) exhibits similar characteristics to the Pacific Decadal Oscillation (PDO) in terms of SST but theirs influences are spatially disparate. TPI utilises SSTs in the South of 20^0N, associated with a 'tripole' pattern and three centres of action and variations, stipulated in the second principal component of a low-pass filtered global SST. Further, vine copulas allows to unite different bivariate copulas for modelling the flexible dependence among pairwise variables independently with the marginal selection (Bedford and Cooke, 2001, 2002; Kurowicka and Cooke, 2006). Vine copulas have not been tested for precipitation forecasting although they were verified for precipitation refinement studies (Liu et al., 2015), stochastic modelling (Verhoest et al., 2015) and daily precipitation disaggregation (Gyasi-Agyei, 2011).

Considering the need for precipitation forecast model to be developed at Australia's Agro-ecological Zones (AEZs), the aims of this study are threefold: (1) to develop a copula-based bivariate and trivariate models describing the joint impact of SOI and TPI on spring seasonal precipitation variability; (2) to evaluate statistically the influence mechanism of the considered climate indices on precipitation through a comparison of the prescribed bivariate and trivariate models; and (3) to evaluate the utility of copula-based conditional model for forecasting seasonal precipitation. The paper is structured as follows. Section 2 covers the theory of copulas; Section 3 presents data, methodology and model development; Section