

1     **Highlights**

- 2     • There are limited studies that analyse observational data of vegetation  
3        feedback on rainfall
- 4     • Two sites with major step trend landuse change were analysed for  
5        changes in rainfall
- 6     • Statistical change in rainfall detected after bushfire, but not after land  
7        clearing

# Analysis of land surface effects on local rainfall using observational data

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## Abstract

Analysis of observational data to identify relationships between rainfall and land cover change are scarce due to multiple environmental factors that cannot be controlled. In this study we investigated the relationship using statistical methods on data from best available sources at two sites in Australia. Gridded data of rainfall and tree cover were used as spatially corresponding local conditions. Large scale effects were represented by climatic indicators, such as SOI and IOD. Regression analysis and step trend tests were used to assess the effect of abrupt land surface intervention. At a Queensland site, dramatic tree cover change between 2002 - 2005 did not result in strong statistically significant precipitation changes. On the other hand, results from step trend test on 1998 - 2008 rainfall data in a bushfire affected NSW/VIC region has a better match with the tree cover change map. This indicates the method works better when a abrupt change in the data can be clearly identified. The results from the step trend test implied a positive relationship between the tree cover and the rainfall at 0.1 significance level.

**Keywords:** Observed data analysis, Rainfall change, Landcover feedback

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Preprint submitted to *Journal of Hydrology* November 20, 2017

## 1. Introduction

Land use and land cover changes can lead to changes in the local climate. Some observational and many modelling studies have found cloud types and rainfall are correlated to large scale vegetation cover changes, such as deforestation in the Amazon and in the Sahel (Chagnon and Bras, 2005; Pinto et al., 2009; Wang et al., 2009; Mei and Wang, 2010; Kucharski et al., 2013; Pitman and Lorenz, 2016) and afforestation in south Israel (Otterman et al., 1990; Ben-Gai et al., 1998). In terms of observational studies, using airborne measurement in Western Australia, Junkermann et al. (2009) showed a significantly higher level of aerosols over an agricultural area compared to an adjacent natural vegetation. They suggested that a modification of aerosol concentrations due to deforestation could have contributed to a reduction of local rainfall, as more but smaller rain droplets were observed. Nair et al. (2011) reported from the Bunny Fence Experiment in Western Australia that local land use change altered the synoptic west coast trough dynamics and surface roughness, and this resulted in the observed rainfall decrease. Climate sensitivity to land cover change is also found in eastern Australia (McAlpine et al., 2007).

Rainfall over land is generally influenced by multiple factors as has been shown from multiple simulation studies. Locally, there are two main sources: moisture from advective atmospheric transport; and local evapotranspiration (Eltahir and Bras, 1996; Bosilovich and Chern, 2006; Dirmeyer et al., 2009; Gimeno et al., 2010). According to Trenberth (1999), the contribution of advective moisture partially depends on the availability of external moisture and atmospheric transport. On the longer time scale, such as monthly and

annually, large scale atmospheric dynamics are affected by large scale climate drivers. Many studies have reported significant relationships between rainfall in large parts of Australia and the El Niño-Southern Oscillation (ENSO) (Verdon et al., 2004; Risbey et al., 2009; Speer et al., 2011). ENSO can be used to represent longer term cycles in rainfall data such as drought. On the other hand, local ET is determined by local land surface characteristics. Local land surface characteristics further influence local scale atmospheric dynamics and hence the amount of rainfall, including contribution from both sources. Therefore land surface plays an important role in local rainfall.

Conventionally, large scale climate drivers are used as predictors for seasonal rainfall forecasts. According to the Australian Bureau of Meteorology (BoM), probabilistic seasonal outlooks are developed based on Australian rainfall and temperature as well as sea surface temperature records from the tropical Pacific and Indian Oceans (BoM, 2012c).

Different parts of the Australian continent can be more or less influenced by different climatic drivers (BoM, 2008). Using both SOI and PDO in a prediction model, Kamruzzaman et al. (2011) reported that PDO was rarely significant for rainfall stations in the MDB and on the southeast coast of Australia, while SOI was at least significant at the 1% level. In addition to SOI, Speer et al. (2011) found that the observed rainfall decrease in the southeast of NSW was linked to an increasingly positive SAM in 1976 - 1998. In southwest WA, the influence of any oceanic indices is small (Smith and Timbal, 2012).

Although climate drivers demonstrate some capability to predict Australian rainfall, there is still a large amount of unexplained variance. Westra

65 and Sharma (2010) pointed out that models based on global sea surface tem-  
66 perature anomalies can only predict up to 14.7% of precipitation variance.  
67 Recent studies suggest that land surface processes are important for pre-  
68 dicting local rainfall (e.g. Ma et al., 2011; Zeng et al., 2012; Pitman and  
69 Lorenz, 2016; Saha et al., 2016). However, they are mostly based on mod-  
70 elling experiments and little evidence was reported from observations. Pit-  
71 man et al. (2004) found a good match between observations and simulated  
72 rainfall changes in southwest Western Australia ,forced by land cover change.  
73 Timbal and Arblaster (2006) were able to reproduce the rainfall decline in  
74 south west Australia by including land cover influence. Local land use change  
75 might not be a primary, but is likely to be a secondary cause of rainfall change  
76 (Nicholls, 2006). Therefore, land surface modification has, at least partially,  
77 contributed to local rainfall variability.

78 Overall the number of observational data studies related to changes to  
79 rainfall due to land cover change is limited. This is because there are some  
80 fundamental experimental difficulties in both space (where does evaporated  
81 water reappear as rainfall?) and in time (how much time does it take for  
82 land cover change effects to appear or disappear?). Therefore, the aim of this  
83 study is to use observational data at regional scales to investigate the cause  
84 and effect relationship between land cover change and local rainfall using  
85 empirical evidence. More specifically, we hypothesize that a step change on  
86 the land cover on the surface will cause a step change in the rainfall and that  
87 this can be identified statistically. To demonstrate the approach and this  
88 effect we studied step changes in rainfall at two locations in Queensland and  
89 NSW/Victoria where there are possible step changes in land cover change due

90 to land clearing and bushfires based on tree cover data. More specifically,  
91 step changes in rainfall were identified statistically, which were subsequently  
92 associated with land cover change through spatial comparison.

93 In this paper, after this section (the introduction), section 2 covers the  
94 case study areas and the observed land use changed. Section 3 describes  
95 the data used in the study in more detail. Section 4 details the statistical  
96 methods and the underlying assumptions related to the modelling approach,  
97 Section 5 gives the results, which are further discussed in section 6 and finally  
98 section 7 offers the conclusions.

## 99 **2. Study regions and tree cover change**

100 In Australia, significant tree cover change has mainly occurred in the  
101 north east of the continent and on the southeast coast, as well as in the  
102 southwest of Western Australia. According to the National Dynamic Land  
103 Cover Dataset (DLCD) (Lymburner et al., 2010), most of these areas have  
104 experienced decreasing EVI between 2000 - 2008. Being a vegetation green-  
105 ness index, the decreasing EVI values indicate lower biomass over time in  
106 the tree cover regions. The EVI reduction is possibly due to land clearing,  
107 bushfires or drought.

108 Two regions were selected where significant tree cover change was present.  
109 One region is located in south central Queensland to the north of the Murray  
110 Darling Basin (MDB) (site 1 in Figure 1). High rates of land clearing have  
111 been reported in this region during the early 2000s (Department of Natural  
112 Resources and Water, 2007). The second study region is located at the border  
113 of New South Wales and Victoria, including the Snowy Mountains range (site

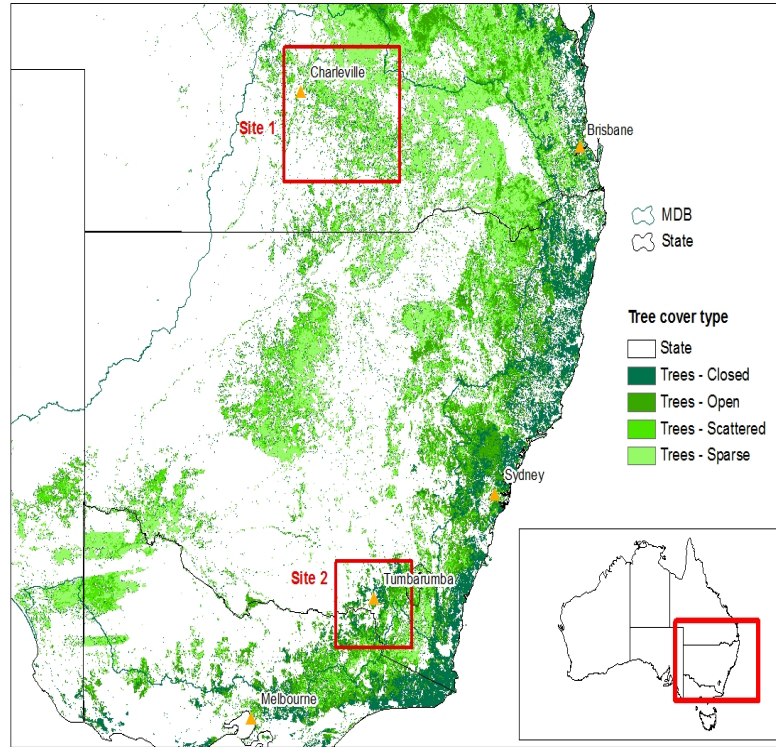


Figure 1: Selected study regions are highlighted by red rectangles in the main map (the red rectangle in the insert indicates the location of the main map). The types of tree cover in 2008 from the DLCD product is shown at the background. In site 1 (the QLD region), the tree cover is mostly sparse. In site 2 (the NSW/VIC region), many areas have open or close forest in which tree cover is denser.

2 in Figure 1). Severe bushfires occurred in this area and the surroundings in  
early 2003 (see Figure 2). The 2003 bushfires were the largest and the worst  
in this area for the last 60 years (The State Government of Victoria, 2011).  
Two thirds of Kosciuszko national park was heavily burned and regrowth was  
reported to be slow due to drought and cold conditions (ABC News, 2003)  
and the type of species in this region. In both study regions, significant tree

cover loss has happened in the last decade, either permanently or temporarily.

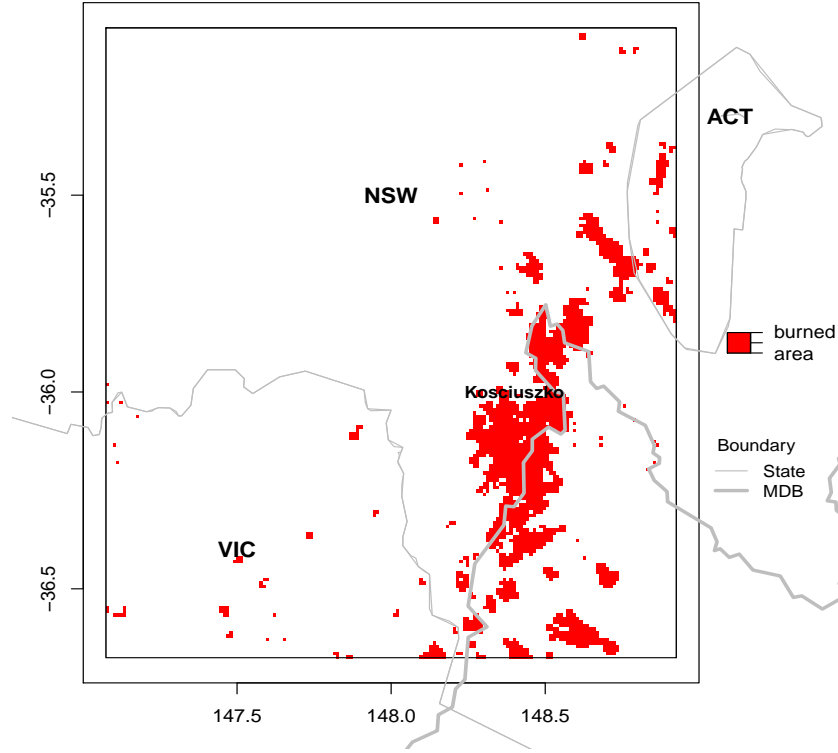


Figure 2: Location of bushfires occurring in January 2003, in and around the NSW/VIC study region, as shown by the red pixels. The map shows large area in the Kosciuszko national park has been burned. Some locations in the southwest of ACT have also experienced intensive bushfires.

The two regions have different climate characteristics. The QLD region is partially grassland and partially subtropical, while the NSW/VIC region is mainly within the temperate zone, under the Köppen classification. According to Australian Bureau of Meteorology (BoM), the NSW/VIC region receives 1000 - 2000 mm rainfall annually, which is more than double of the rainfall in the QLD region. Evapotranspiration is similar in both regions.



127 Marine moisture and orographic effects are likely to be the main contributors  
128 to rainfall in the southeast mountain areas of the NSW/VIC region.

129 The land use and land cover characteristics in the two regions are also  
130 different. In the Queensland region, the tree cover is sparse over most of the  
131 area. The MODIS satellite tree cover data (discussed in more detail in section  
132 3) shows that tree cover in this region is generally below 20% of total ground  
133 area. Grazing is the main activity in this region, with over 90% of land used  
134 by the grazing industry (ABARES, 2010). Our starting assumption is that  
135 the main cause of the EVI decline over large part of the region is due to land  
136 clearing. Tree cover has been cleared at a massive scale over the last decade,  
137 especially during 2002 - 2004.

138 The Kosciuszko national park is within the NSW/VIC region. Here tree  
139 cover is denser with open or closed forest (the tree cover distribution is bi-  
140 modal at 10 - 20% and 60 - 70%). The dominant species in the alpine area  
141 are Snow Gum and large stand species such as Alpine Ash and Mountain  
142 Gum in the sub-alpine area. These trees can reach a great height but they  
143 take long time to grow. For example, Alpine Ash would need about 20 years  
144 to mature. Although land clearing is not a major issue in this region, it is  
145 vulnerable to fires and drought.

146 Therefore two types of land cover changes were studied. The reports  
147 from the Queensland Statewide Land Cover and Trees Study (SLATS) (e.g.  
148 Department of Natural Resources and Mines, 2005, 2006) were used to in-  
149 vestigate the time and location of land clearing in the QLD region. The  
150 MODIS burned area product, MCD45A1 (Roy et al., 2002, 2005, 2008), was  
151 used to locate bushfires areas in the NSW/VIC region, with a grid resolution

152 of 500 m. MCD45A1 provides monthly burning information on all pixels,  
 153 which helps to pinpoint an abrupt event. Due to the nature of the different  
 154 land cover change, the post-change vegetation status in the two regions is  
 155 expected to be different (see Figure 3).

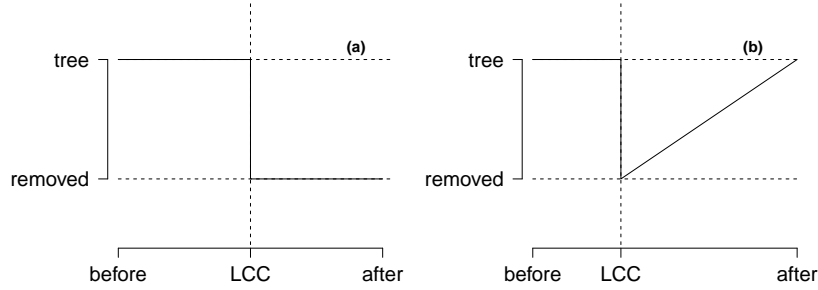


Figure 3: The expected evolution of the land surface after trees have been removed in (a) the QLD region and (b) the NSW/VIC region.

156 Specifically, this study focused on the effect of 2003 - 2004 land clearings  
 157 in the QLD region and the effect of 2003 bushfires in the NSW/VIC region.  
 158 These events are expected to cause a step change in the local rainfall. The  
 159 actual tree cover change at the pixel level during this time was derived from  
 160 the 11-year MODIS data (discussed below). The difference of tree cover  
 161 before and after the land disturbance was tested using a Student's t-test. As  
 162 the length of the tree cover data is shorter than the length of the rainfall  
 163 data, earlier land clearings in the QLD region cannot be identified spatially,  
 164 hence they are excluded from the analysis.

### 165 3. Data

166 Two land surface data sets were used in this study. The main one was the  
167 MOD44B product Global Vegetation Continuous Field dataset (version 5).  
168 This dataset provides estimates of percent tree cover (percentage of ground  
169 surface covered by trees) at a grid resolution of 250 m (Townshend et al.,  
170 2011), which is finer than the earlier mentioned burned product MCD45A1.  
171 The dataset is available on an annual time interval for the period of 2000  
172 - 2010. The National Dynamic Land Cover Dataset (DLCD) (Lymburner  
173 et al., 2010) from the Australian Collaborative Land Use Mapping Program  
174 (ACLUMP) was used to verify the trend of vegetation cover change calculated  
175 from the previous dataset. This dataset, developed by Geoscience Australia  
176 and Australian Bureau of Agricultural and Resource Economics and Sciences  
177 (ABARES), is the first nationally consistent and thematically comprehensive  
178 land cover reference for Australia. The DLCD is based on the 16-day En-  
179 hanced Vegetation Index (EVI), again from the MODIS satellite, between  
180 April 2000 and April 2008. It also has a grid resolution of 250 m. The  
181 dataset provides information on the final land cover types (as in 2008) and  
182 estimated trend of EVI statistics (annual mean, maximum and minimum).

183 Rainfall data for Australia (Jones et al., 2009) was obtained from BoM.  
184 The data has been projected onto a national  $0.05^\circ \times 0.05^\circ$  grid (approximately  
185  $5 \text{ km} \times 5 \text{ km}$ ). This gridded dataset was generated from station observa-  
186 tions using an optimised Barnes successive correction technique. The Barnes  
187 technique combines a weighted averaging process and defined topographical  
188 information to estimate rainfall values between spatial points (BoM, 2009).  
189 The resulting dataset provides additional information for data-sparse areas

190 like central Australia but reduces information in the data-rich areas, such as  
191 southeast Australia where station density is up to 20 per 100 km<sup>2</sup>. The data  
192 is available on a monthly basis from 1900 to current. Here a subset of 30  
193 years (1979 - 2008) was used. The study was conducted on monthly data,  
194 as a land cover change effect on annual rainfall might be negligible but can  
195 often found to be significant in particular months or seasons (e.g. Otterman  
196 et al., 1990; Gaertner et al., 2001; Semazzi and Song, 2001; Oleson et al.,  
197 2004; Deo et al., 2009).

198 Large scale climate drivers are represented by various climatic indices.  
199 The Southern Oscillation Index (SOI) is generally regarded as a good pre-  
200 dictor for Australian rainfall (Risbey et al., 2009; Chowdhury and Beecham,  
201 2010; Westra and Sharma, 2010), but its skill is weaker in some parts of Aus-  
202 tralia. For example the Southern Annular Mode (SAM) is found to be more  
203 important than ENSO in south Western Australia (Meneghini et al., 2007).  
204 The suitability of each index for the study regions is analysed in detail in  
205 section 4.1. The following climate indices were tested as predictors for local  
206 rainfall.

- 207 • Southern Oscillation Index (SOI). The Troup version of the monthly  
208 SOI series used in this study was obtained from BoM (available online  
209 at <http://www.bom.gov.au/climate/current/soihtm1.shtml>).
- 210 • Eastern, East Central and Central Tropical Pacific Sea Surface Tem-  
211 peratures (NINO 3, NINO 3.4 and NINO 4). Monthly SST anomalies  
212 are available from IRI/LDEO data library and the extended NINO  
213 dataset is used (available online at <http://iridl.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/>).
- 214

- 215 • Pacific Decadal Oscillation (PDO). The Pacific Decadal Oscillation  
216 is the leading principal component of monthly SST anomaly in the  
217 North Pacific Ocean.. The monthly PDO series was provided by JISAO  
218 (Joint Institute for the Study of the Atmosphere and Ocean, University  
219 of Washington) (available online at [http://jisao.washington.edu/](http://jisao.washington.edu/pdo/PDO.latest)  
220 [pdo/PDO.latest](http://jisao.washington.edu/pdo/PDO.latest)).
- 221 • The interaction of PDO and SOI (PDO $\times$ SOI) (Kamruzzaman et al.,  
222 2011).
- 223 • Indian Ocean Dipole (IOD). The Indian Ocean dipole is commonly mea-  
224 sured by the difference between SST anomaly in the western (50 - 70°E  
225 and 10°S-10°N) and eastern (90 - 110°E and 0 - 10°S) equatorial India  
226 Ocean (Saji et al., 1999). Monthly IOD was obtained from JAMSTEC  
227 (the Japan Agency for Marine-Earth Science and Technology) (avail-  
228 able online at [http://www.jamstec.go.jp/frcgc/research/d1/iod/](http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi.monthly.txt)  
229 [DATA/dmi.monthly.txt](http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi.monthly.txt)).

#### 230 4. Statistical method

231 As shown in Figure 4, a step change is not obvious in the time series  
232 data, even though the data is deseasonalised and detrended. Hence, the step  
233 changes in the rainfall were analysed using two different statistical methods  
234 to provide a comparison. Both methods make use of a regression model to  
235 remove variability in rainfall hypothesised to be caused by factors other than  
236 vegetation cover change. In the first method, the tree cover change was im-  
237 plemented as a factor variable in the regression model. In the second method,

238 a rank sum test (step trend test), was applied to the model residuals after  
 239 effects of other major factors have been removed, assuming that vegetation  
 240 cover change is the only factor explaining the non-random pattern in the  
 241 rainfall residuals.

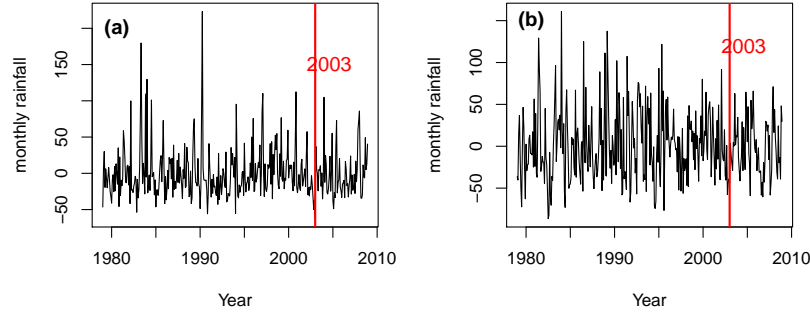




Figure 4: The deseasonalised and detrended rainfall over the 30 years period in (a) the QLD region and (b) the NSW/VIC region. The vertical red lines indicate the year of 2003, in which the studied land cover changes occurred. A change in the time series data is not obvious before and after the land cover changes.

#### 242 4.1. Regression model

243 Rainfall is generally affected by several factors. Many studies suggest the  
 244 large-scale climate drivers, which are related to the global or regional atmo-  
 245 spheric air mass movement, are the dominant control on the overall rainfall  
 246 (Maynard and Polcher, 2003; DeAngelis et al., 2010; Holper, 2011; Smith  
 247 and Timbal, 2012). Long term trends are shown in Australian rainfall, and  
 248 this has been linked to global climate change (Cai et al., 2014; Delworth and  
 249 Zeng, 2014; Holper, 2011; Karoly, 2014). The difference in available radia-  
 250 tion and hence ET in different seasons increase the variability in rainfall. The

251 land surface effect on rainfall can be confused by changes in these factors.  
252 Hence a regression model was used to estimate the amount of variability in  
253 rainfall that is due to these important factors, and isolate changes resulting  
254 from local vegetation cover change. As highlighted in the introduction, the  
255 Australian climate is influenced by sea surface temperature in the tropical  
256 Pacific and Indian Oceans, as well as pressure systems in the Southern Ocean  
257 (BoM, 2012b). Risbey et al. (2009) compared five large-scale drivers, includ-  
258 ing ENSO (measured by SOI and the Tropical Pacific SSTs), IOD, SAM,  
259 MJO<sup>1</sup> (Madden-Julian oscillation) and blocking, in relation to Australian  
260 rainfall variability. They identified SOI as the most important index among  
261 all indices tested for broad parts of Australia (including QLD and NSW/VIC)  
262 in almost any season. In this study, up to two important indices identified  
263 from the seven climatic indicators (see section 3) were used, for each study  
264 region, as the explanatory variables in the model .

265 As a preliminary step, the correlations between rainfall and each climatic  
266 index were analysed. Rainfall in each study region was first deseasonalised  
267 and detrended using the seasonal decomposition function "stl" in R (R Devel-  
268 opment Core Team., 2011).  Detrending is needed to remove the correlations  
269 between trends in the data as discussed in Smith and Timbal (2012). The  
270 cross-correlations between the deseasonalised and detrended rainfall and the   
271 climatic indices were tested using the Pearson's product moment correla-  
272 tion method, assuming the relationships are linear. Although the optimal  
273 technique for exploring the correlation with each index could be different as

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<sup>1</sup>MJO is a large scale eastward-propagating wave-like disturbance in equatorial latitudes (Risbey et al., 2009).

described in Risbey et al. (2009), ~~the~~ Pearson's method was ~~applied to~~ all indices for consistency. Because the PDO is a low frequency descriptor of the multi-decadal SST (MacDonald and Case, 2005; Zanchettin et al., 2008; Kamruzzaman et al., 2011) a longer period (108 years, from 1900 to 2008), instead of 30-year rainfall data, was used to estimate the correlation with PDO, up to lag 24. For the other indices, the 30-year rainfall data set was used.

Based on the correlation between the climatic indices and rainfall (as shown in Figure 5 and Figure 6), the following ~~results were found~~:

- In QLD, the correlation between rainfall and SOI at zero time lags is the highest across all indices, outweighing the other ENSO indicators.
- In NSW/VIC, ~~again~~ the SOI has the highest correlation with rainfall, closely followed by the IOD. Both occur at ~~the~~ zero time lags.

The above findings are consistent with previous studies. Although some indices are serially correlated with rainfall up to several months, the lag zero events have the most significant correlation coefficients. Concurrent climatic index series were generally found most useful in rainfall prediction (e.g. Risbey et al., 2009; Kamruzzaman et al., 2011). **The correlations between the**

**climatic indices and rainfall for each individual season have also been tested.**

SOI was used in the Qld prediction, SOI and IOD were used in the NSW/VIC prediction.

Rainfall in Australia shows strong seasonal patterns (Holper, 2011; Australian Bureau of Statistics, 2012). For example, the north part of the country is summer rainfall dominant with dry winter, while most of the southern part has a winter rainfall regime. This ~~character is given~~ by the movement



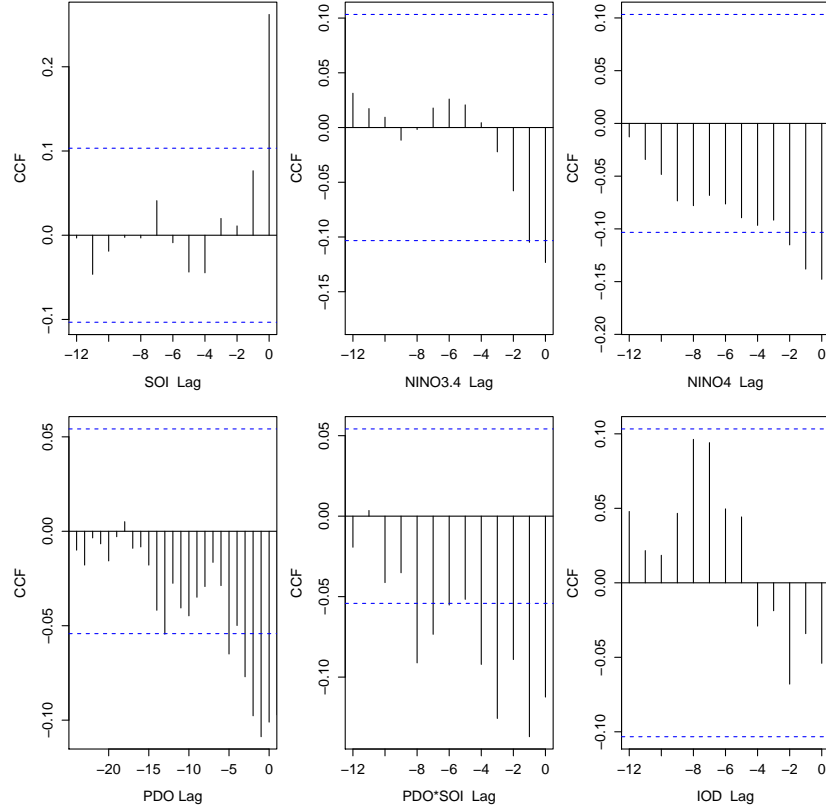


Figure 5: Cross-correlation of the six indices and rainfall in QLD study region. Where the correlations with PDO are sought, 108-year rainfall data (1900 - 2008) are used. Otherwise, 30-year rainfall data are used. The correlation with NINO 3 is not shown as it is very similar to but weaker than the case of NINO 3.4. The blue dashed lines indicate the 95% confidence interval.

of subtropical high pressure system which dominates the Australian climate  
 (BoM, 2012a). The seasonal component of rainfall has a periodic pattern so  
 it is better modelled as a smooth term. A spline function was applied on the  
 months to define a smooth seasonal pattern (Wood, 2011).

Long term trends in the regional rainfall in some parts of Australia are

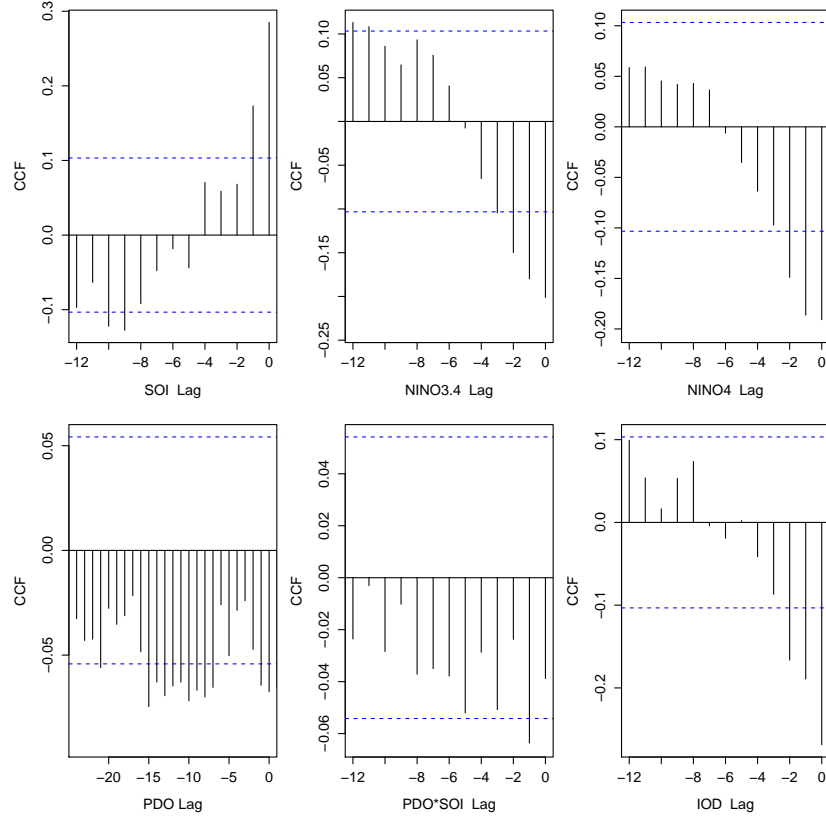


Figure 6: Cross-correlation of the six indices and rainfall in NSW/VIC study region.

304 significant (Hughes, 2003; Gallant et al., 2007; Chowdhury and Beecham,  
 305 2010). In the northern and eastern parts of the continent, increasing rainfall  
 306 is reported over the last century (Hughes, 2003). The presence of such long  
 307 term trends may be confused with the outcome of a step change in rainfall.  
 308 A linear trend term was implemented in the model to remove any long term  
 309 trend effect.

310 We assumed all the factors are additive components in determining rain-  
 311 fall as in Kamruzzaman et al. (2011). Generally, monthly rainfall has a

312 skewed distribution so the normality assumption of the residuals in a general  
 313 linear model could be violated. In this case, the rainfall model is expressed  
 314 as a generalised additive model (GAM) (Hastie and Tibshirani, 1986) with  
 315 a log link function  $g()$ , assuming the residuals are gamma distributed (see  
 316 Figure 7).

$$g(E(\mathbf{R}_r)) = \beta_0 + s_1(D_{1,r}\mathbf{SOI}) + s_2(D_{2,r}\mathbf{IOD}) + s_3(\mathbf{Season}) + \beta_1\mathbf{Trend} + \epsilon_r \quad (1)$$

317  
 318 The bold letters represent the time series vectors. The subscript  $r$  denotes  
 319 the region,  $r = \text{qld}$  or  $\text{nswvic}$ .  $\beta_u$  ( $u=0, 1$ ) are the fitted coefficients in the  
 320 model.  $s_v$  ( $v=1, 2, 3$ ) are the smooth functions on the climatic indices and  
 321 the season.  $D_{1,r}$  and  $D_{2,r}$  switch on/off the corresponding climatic index in  
 322 the model as discussed previously.

$$D_{1,r} = 1 \quad (2)$$

324 as SOI was used in both regions as rainfall predictor.

$$D_{2,r} = \begin{cases} 1 & \text{for NSW/VIC} \\ 0 & \text{for QLD} \end{cases} \quad (3)$$

326 The linear long term trend in the rainfall data is modelled by  $\mathbf{Trend}=1,2,3\dots n$ ,  
 327 where  $n$  is the total number of months in the time series.  $\mathbf{Season}$  is the sea-  
 328 sonal component which is represented by applying a smooth spline function  
 329 on the month values (1-12). The monthly rainfalls in both regions appear to  
 330 have a lag 1 autocorrelation, being 0.26 for QLD and 0.33 for NSW/VIC.  
 331 The SOI and IOD terms are also modelled with spline functions. As the  
 332 effect of large scale drivers on Australian rainfall is more likely to be seasonal

333 (Murphy and Timbal, 2008; Schepen et al., 2012), the spline function can  
 334 closely reproduce the high and low impacts of the climatic indices.

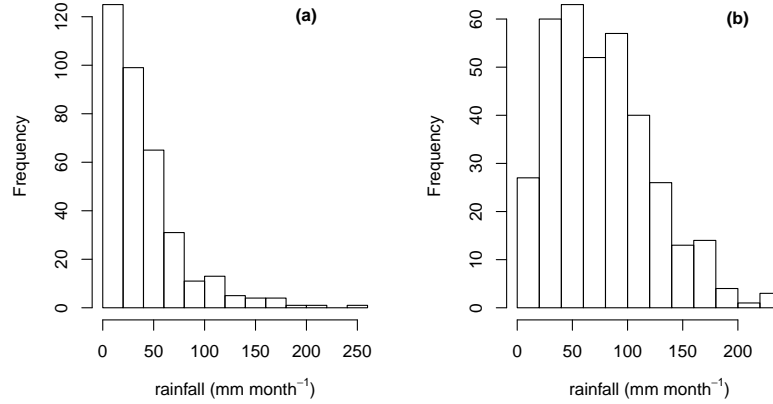


Figure 7: Distribution of monthly rainfall in (a) QLD and (b) NSW/VIC. By using a Kolmogorov-Smirnov test with shape = 1 and 2.4 respectively, rainfalls in both regions are shown to have a gamma distribution.

#### 335 4.2. Tree cover change as factor variable

336 One of the main difficulties in empirical observation studies on the ef-  
 337 fect of land cover change on rainfall is the lack of continuous monitoring of  
 338 land surface variables, or even, no specific variable can be defined to clearly  
 339 represent the land surface process. Given the lack of a full picture of the  
 340 land surface process, a factor variable was used in this study to represent the  
 341 abrupt land surface change (see Equation 5). The change could be a result  
 342 of either land clearing or bushfires as long as it is permanent or takes a long  
 343 time to recover. Here we approached the problem with two different models.

344 In the first method, the tree cover change was used as a predictor in the  
 345 regression model, represented by a factor variable **LC**. The significance of  
 346 the coefficient of **LC**, denoted as  $\beta'_2$  in Equation 5, can be determined by a  
 347 ratio test.

$$348 \quad LC = \begin{cases} \text{Trees} \\ \text{Removed} \end{cases} \quad (4)$$

349 Therefore in both regions, land cover is “trees” for the period before land  
 350 cover change and “removed” for the period after the change. Here we sim-  
 351 ply assumed that vegetation cover change has occurred on every pixel. The  
 352 remaining term  $\epsilon_r$  is the amount of rainfall that is attributed to other un-  
 353 specified factors and random errors. Hence the regression model becomes  
 354

$$355 \quad g(E(\mathbf{R}_r)) = \beta'_0 + s'_1(D_{1,r}\mathbf{SOI}) + s'_2(D_{2,r}\mathbf{IOD}) + s'_3\mathbf{Season} + \beta'_1\mathbf{Trend} + \beta'_2\mathbf{LC} + \epsilon'_r \quad (5)$$

356 Vegetation cover changes occurred at different times in the two regions.  
 357 In the QLD region, there no exact time can be assigned to the land clear-  
 358 ing. Clearing has occurred between 2003 - 2004 according to SLATS reports.  
 359 The information on the change in type of land cover during this time period  
 360 is missing. Therefore, four scenarios were tested in the analysis. In these  
 361 scenarios the “after change” period started from: (1) June 2003, (2) January  
 362 2004, (3) June 2004 and (4) January 2005. In the NSW/VIC region, se-  
 363 vere bushfires were reported in early January 2003. Hence the “tree” cover  
 364 state was up to December 2002 then it was changed to “removed” state from  
 365 January 2003. The regression model was run from 1979 for both regions.

### 366 4.3. Step trend test

367 As a second method, a step trend test was used to detect changes in rain-  
368 fall after the vegetation cover change. This nonparametric statistical test  
369 was modified from the Mann-Whitney Rank-Sum test by Hirsch and Gilroy  
370 (1985). The test was developed to look for a step change in data which is  
371 cross correlated. As the gridded rainfall dataset is based on an interpolation  
372 method, this results in a high spatial correlation between neighbouring pix-  
373 els. The step trend test is suitable for the analysis of such a dataset. The  
374 advantages of this test are: (1) it does not depend on assumptions of the  
375 data distribution; (2) it is not restricted to datasets with no missing data;  
376 (3) it is robust and not as easily influenced by outliers and negative numbers  
377 (Hirsch and Gilroy, 1985).

#### 378 4.3.1. Rainfall residuals

379 The rainfall residuals from the regression model in Equation 1 were used  
380 for this test. According to Hirsch and Gilroy (1985), using deseasonalised and  
381 detrended data is important in a test to detect step change. Furthermore,  
382 since rainfall is only partially attributed to local sources and conditions, noise  
383 can be introduced by large scale dynamics and changes in other climatic  
384 factors. The assumption is that the regression model should remove this  
385 noise. Hence the model residuals  $\epsilon'_r$  exclude the effects due to climate drivers,  
386 seasonality and the long term trend. As a result local effects are assumed  
387 to explain at least part of the variation in the residuals. The test, described  
388 in the following section, associates changes in rainfall with the tree cover  
389 changes.

390 *4.3.2. Mann-Whitney rank-sum statistic*

391 The step trend test is a modified version of the Mann-Whitney rank-sum  
 392 statistic (Hirsch and Gilroy, 1985). As a nonparametric rank-based test, the  
 393 Mann-Whitney test does not use the exact values of rainfall but depends on  
 394 the ranks of the data. For each month, rainfall residuals of each year were  
 395 ranked in an ascending order. The ranking of January rainfall in a sample  
 396 pixel  $k$  in QLD is illustrated below:

	1998	1999	2000	2001	2002	2005	2006
Rainfall residuals:	-0.3	-60.9	-16.1	-71.7	111.1	-7.2	-60.5
Rank ( $R'_{1k}$ ):	6	2	4	1	7	5	3

397 Therefore, the smallest value (including negative values) has rank 1 and  
 398 the largest value has the maximum rank.

399 The before period and the after period formed two groups of samples.  
 400 The split point of the two periods was based on the timing of the vegetation  
 401 cover changes. In the QLD region, changes occurred anytime during 2003  
 402 and 2004. In contrast to the previous method, the time period of where the  
 403 land cover change occurred was excluded, as the nonparametric test allows  
 404 missing data. Hirsch and Gilroy (1985) also pointed out that the power of  
 405 the test is higher if the data of the change period is ignored. Hence 2003 and  
 406 2004 were excluded from the analysis. As a result, the after-change period  
 407 was 2005 - 2007.

408 In the case of NSW/VIC, the bushfires broke out in early January 2003.  
 409 The change was within a relatively short period of the year. Therefore the  
 410 after-change period in this region still started in January 2003. The before

411 period was set to five years (1998 - 2002) in both regions.

412 The rank of rainfall in month  $j$  year  $i$  in pixel  $k$  is denoted as  $R'_{ijk}$ . The  
 413 sum of ranks of rainfall in month  $j$  in pixel  $k$  before the known intervention  
 414 is:

$$415 \quad W_{jk} = \sum_{i=1}^{n_1} R'_{ijk}. \quad (6)$$

416  $n_1$  is the number of years before the land cover change. The expected value  
 417 of  $W_{jk}$  is

$$418 \quad \mu_w = n_1(n_1 + n_2 + 1)/2 \quad (7)$$

419  $n_2$  is the number of years after the change. Hence the expected value of the  
 420 rank sum before the intervention is the same for all months and all pixels.  
 421 The sum of ranks for the whole time period is fixed, as  $(n_1 + n_2)(n_1 + n_2 + 1)/2$ .  
 422 Knowing the rank-sum of one group the rank-sum of the other group can be  
 423 easily derived. If the rainfall data is temporally and spatially independent,  
 424 the variance of  $W_{jk}$  is

$$425 \quad \sigma_w^2 = n_1 \cdot n_2(n_1 + n_2 + 1)/m \quad (8)$$

426 where  $m$  is the number of months which is 12 in the case of a full year.

#### 427 4.3.3. Step trend test

428 Instead of completing the Mann-Whitney U-test, Hirsch and Gilroy (1985)  
 429 applied the rank-sum statistics in a standard normal Z test. The modified  
 430 test can be used to detect step change and it accounts for serial and cross  
 431 correlation in the data. In the case here, the deseasonalised and detrended  
 432 data shows little autocorrelation in the time series but possesses strong cross  
 433 correlation between neighbouring pixels, i.e.  $R > 0.99$ . Hence the covariance  
 434 between pixels would need to be considered in the test.



435 The sum of  $W_{jk}$  for a block of  $ns$  pixels over the whole year,  $\sum_{j=1}^{12} \sum_{k=1}^{ns} W_{jk}$ ,  
 436 has a mean value of

$$437 \quad E\left(\sum_{j=1}^{12} \sum_{k=1}^{ns} W_{jk}\right) = 12 \cdot ns \cdot \mu_W \quad (9)$$

438 and variance

$$439 \quad Var\left(\sum_{j=1}^{12} \sum_{k=1}^{ns} W_{jk}\right) = \sum_{j=1}^{12} \sum_{k=1}^{ns} \sum_{h=1}^{ns} C(W_{jk}, W_{jh}). \quad (10)$$

440  $C(W_{jk}, W_{jh})$  is the covariance of the  $W$  statistics between pixel  $k$  and pixel  
 441  $h$  in month  $j$ . When  $k = h$ ,  $C(W_{jk}, W_{jh}) = \sigma_w^2$ . When  $k \neq h$ ,

$$442 \quad C(W_{jk}, W_{jh}) = \sigma_w^2 r(R_k, R_h) \quad (11)$$

443 where  $r(R_k, R_h)$  is the product moment correlation coefficient of the concur-  
 444 rent ranks in pixel  $k$  and  $h$ . Here  $r$  is calculated on the full time series in  
 445 each pixel. In this analysis, the test was applied to a square block of four  
 446 pixels each time. As argued by Hirsch and Gilroy (1985),  $ns = 4$  is the most  
 447 optimal solution to balance the cost and the gain in the test power.

448 The statistic of the step trend test is then defined as

$$449 \quad Z' = \frac{\sum_{j=1}^{12} \sum_{k=1}^{ns} W_{jk} - 12 \cdot ns \cdot \mu_w}{\sqrt{Var(\sum_{j=1}^{12} \sum_{k=1}^{ns} W_{jk})}}. \quad (12)$$

450 The above statistic is written for a 12 month period. The statistic can also  
 451 be used to test seasonal rainfall change or for other customized periods, by  
 452 changing the value 12.

453 The null hypothesis ( $H_0$ ) in this study is that there was no change in  
 454 rainfall due to land surface intervention. The results of the step trend test  
 455 can be interpreted according to the sign of  $Z'$  score (see Table 1).  $Z'$  is

Table 1: The interpretation of  $Z'$  score in the step trend test. Following Hipel and McLeod (1994, Chapter 23, P887).

---

$Z' > 0$	rainfall decreases after change
$Z' < 0$	rainfall increases after change
$Z' = 0$	rainfall does not change

---

456 normally distributed similar to the standard normal statistics  $Z$ . Hence it  
457 can be compared to a standard normal distribution to determine the p value.

## 458 5. Results

### 459 5.1. Tree cover changes

460 The pixels with significant tree cover change in each study region are  
461 shown in Figure 8, at the  $p < 0.1$  significance level. Despite the limitations of  
462 the length of this data series, it still indicates a large change in the NSW/VIC  
463 region. In the NSW/VIC region, much of the tree loss between 2002 and 2003  
464 was in the Snowy Mountains which are at the border of NSW and VIC. Tree  
465 cover loss occurred in large parts of the QLD study region between 2002  
466 and 2005. Most of the clearings appear in the centre of this region. The  
467 tree cover change map is consistent with the annual mean EVI trend map  
468 (based on DLCD data, map not shown here), which confirms these changes  
469 are significant and persistent over the study period.

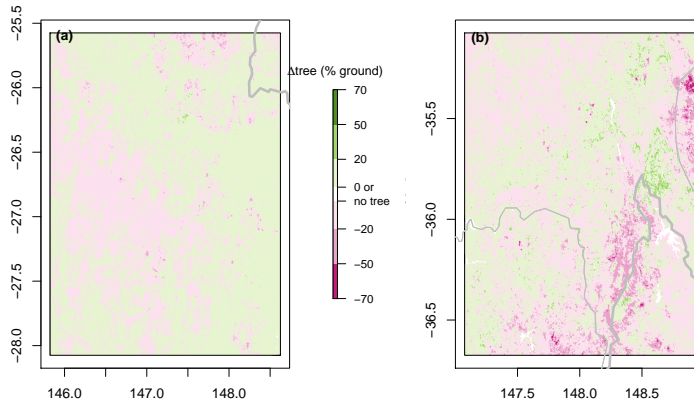


Figure 8: The maps show the areas with significant changes in tree cover (at  $p < 0.1$ ) in (a) the QLD region and (b) the NSW/VIC region. The amount of change was calculated as the difference in tree covers before and after the specified land cover intervention and it is shown as the percentage of the ground area. Green colour indicates an increase in tree cover, while red colour indicates a decrease in tree cover.

## 470 5.2. Regression Model & Significance of Vegetation Cover Changes

471 The regression model does not explain much of the rainfall variability.  
 472 The model in Equation 5 accounts for around 13%<sup>2</sup> of the rainfall variations  
 473 in the QLD region and 19% in the NSW/VIC region on average. The resid-  
 474 ual analysis shows that the assumptions of the regression model are generally  
 475 met. The standardised residual plots, however, show some funnelling for the  
 476 NSW/VIC regions, suggesting non constant variance. The residual analy-  
 477 sis, based on one sample pixel from each region, in Figure 9 and Figure 10  
 478 illustrates this. The residual patterns are consistent within each region.

---

<sup>2</sup>Here the adjusted  $R^2$  was reported. Adjusted  $R^2$  is the coefficient of determination, a measurement of the amount of variability predicted by the model adjusting for the number of explanatory terms

479 The model confirms the importance of the climate drivers and the sea-  
 480 sonality in Australian rainfall. Even at the grid level, the seasons and the  
 481 climatic indices were significant ( $p < 0.05$ ) in both regions. The explaining  
 482 power of the model is mostly due to these variables. The climate drivers (at  
 483 lag zero) accounted, on average, for 6% of the rainfall variability in both the  
 484 QLD region and the NSW/VIC region (see Figure 11 for the distribution  
 485 of  $R^2$  in these two regions). These figures are within the upper bound of  
 486 seasonal rainfall predictability by SST anomaly field reported by Westra and  
 487 Sharma (2010).

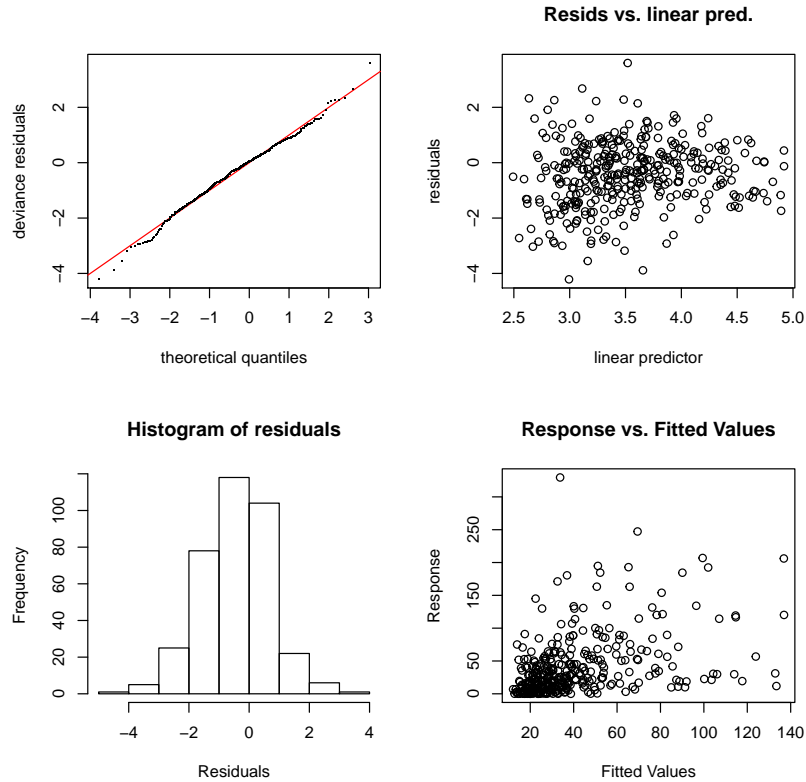


Figure 9: The residual analysis of a sample pixel in the QLD region.

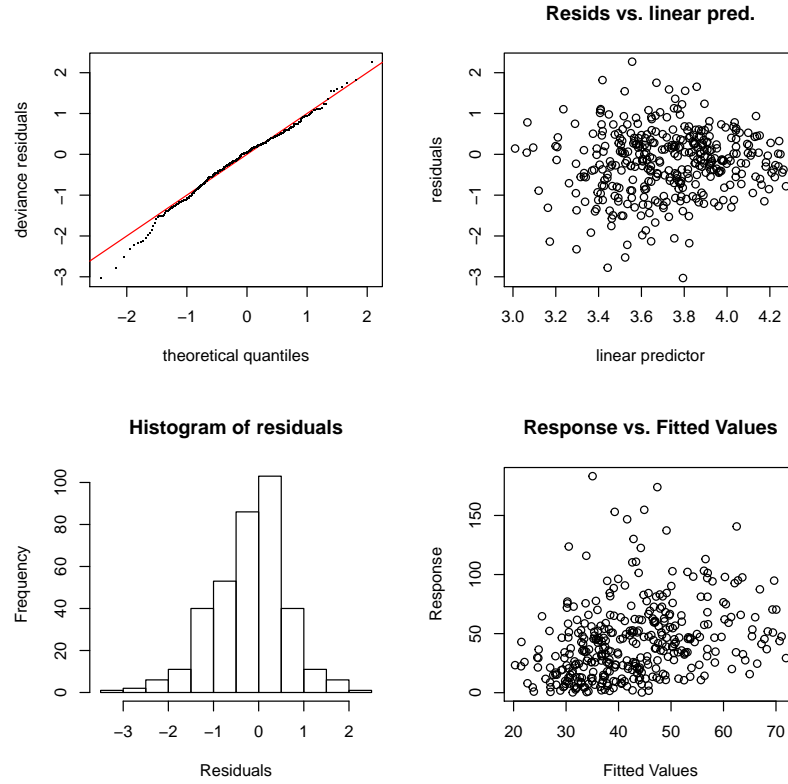


Figure 10: The residual analysis of a sample pixel in the NSW/VIC region.

488 A statistically significant long term trend was not observed in either of  
 489 the two regions. However, this result does not disprove the importance of a  
 490 long term trend in rainfall. The overall time period is fairly short and more  
 491 pixels in NSW/VIC would have a significant step change if the long term  
 492 trend effect is not removed by the model. As trend free data is an important  
 493 requirement for the step trend test, the trend term was kept in the regression  
 494 model to ensure the detection of step change was not due to a possible long  
 495 term trend.

496 The land cover variable implies a step change with different values before

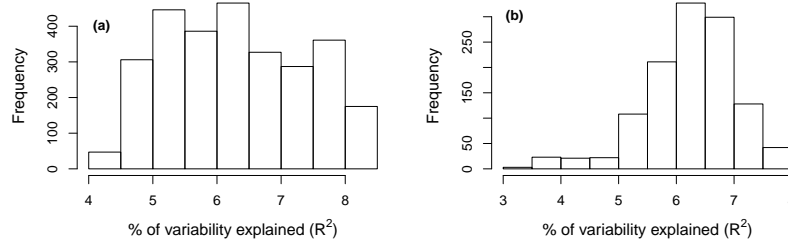


Figure 11: The distribution of  $R^2$  when rainfall is only modelled by the climate drivers. It shows the percentage of rainfall variability that can be explained by the climate drivers. In the case of (a) the QLD region, SOI was the only climatic index considered. In (b) the NSW/VIC region, SOI and IOD were used.

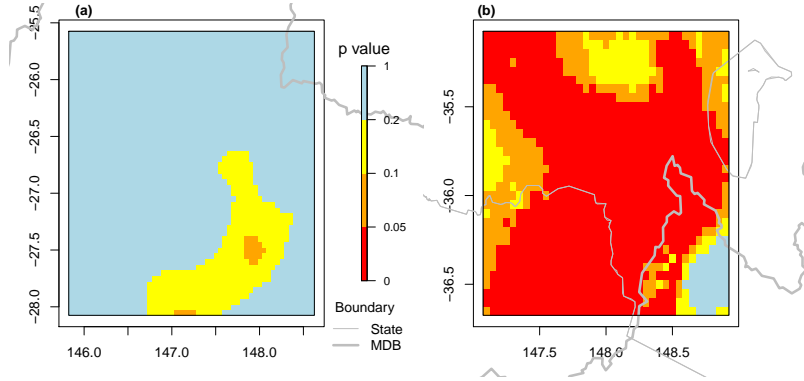


Figure 12: The spatial distribution of significance of vegetation cover changes in the two study regions. The significance of vegetation cover changes is assessed in the regression model. The figures report the p values of the coefficient of the land cover variable in the model at different significance level. The plot of the QLD region is for the scenario that the after change period started from January 2005, as the other scenarios don't have any p value less than 0.2.

497 and after the land cover intervention. This variable was only significant  
 498 ( $p = 0.05$ ) for the rainfall estimates in some areas in NSW/VIC, as shown

499 in Figure 12 (b). The effect of tree removal in the NSW/VIC region was  
500 highly significant in the area from the Snowy Mountains range in the south  
501 to the west side of Australian Capital Territory (ACT), highlighted by the  
502 red colour in Figure 12 (b). However no significant step change (at  $p < 5\%$ )  
503 due to the land cover changes was found in rainfall of the QLD region in any  
504 of the four scenarios.

505 In the NSW/VIC region, the locations of rainfall change show some agree-  
506 ment with the locations of vegetation cover change. Comparing the results  
507 in Figure 12 (b) to Figure 8 (b), the alpine area with massive tree cover  
508 loss is located inside the highlighted region. The results show that the step  
509 change in rainfall also occurred in the cotter river catchment which was heav-  
510 ily burned in 2003 bushfires (refer to Figure 2). However, Figure 12 (b) also  
511 shows that a significant step change in rainfall was found in an area larger  
512 than where the bushfires has occurred. From this point of view, the results  
513 might be showing a large scale effect that extends beyond the vegetation  
514 cover change effect.

515 More generally, the model also shows that the tree cover has a positive  
516 impact on rainfall. The fitted coefficients for the reference state "trees" were  
517 consistently positive for the pixels whose step changes of rainfall were signif-  
518 icant. It implies that rainfall was higher when the surface was covered by  
519 trees. This was confirmed by applying a two sample Student's t-test on the  
520 annual rainfall of the before-change and after-change periods.

### 521 5.3. Step Trend Test

522 The spatial step trend test  $Z'$  scores are shown in Figure 13. This figure  
523 provides two types of information: the sign and the significance level. The

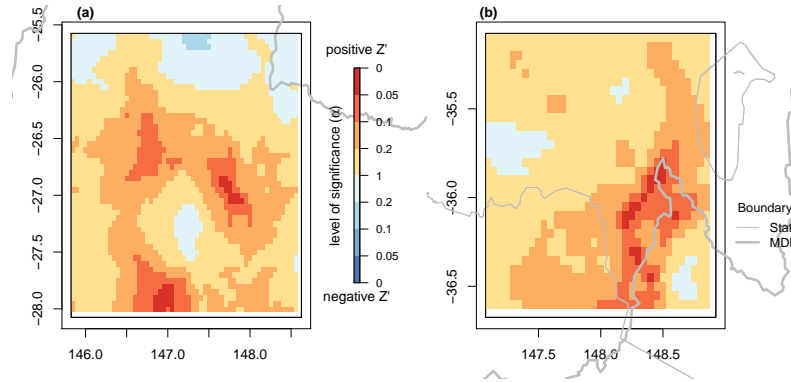


Figure 13: Spatial distribution of the step trend test  $Z'$  statistics in the two study sites. The test was conducted on the 30-year rainfall data from 1979 to 2009. Warm colours (yellow, orange and red) are for positive  $Z'$  values which indicate decreasing rainfall trend due to the land surface intervention. Cold colours (light blue to blue) are for negative  $Z'$  values which indicate increasing rainfall trend. The deeper the colour, the more significant the statistic.

sign indicates the direction of the step change, as listed in Table 1. In each region, there is a broad area of positive  $Z'$  values which implies a decrease in rainfall. In QLD, the areas of positive  $Z'$ , especially when  $p$  is smaller than 0.1, almost align with the locations reported to have heavy land clearing (see Figure 14). However the vegetation cover change map in Figure 8 (a) does not indicate a clear similar pattern. In the Snowy Mountains area and the west of ACT, where severe bushfires occurred in 2003, positive  $Z'$  values were also found. It again indicates that loss of tree cover was related to a rainfall decrease. Nevertheless the observed step change in rainfall was not strong. At the 5% significance level, changes in a number of pixels in the alpine area are possibly where the tree recovery is slow. In the QLD region, 35 pixels obtained a  $Z'$  score with  $p < 5\%$ . In the NSW/VIC region, there are only



18 pixels in the alpine area having a  $Z'$  score with  $p < 5\%$ . They are a very small proportion of both study regions. As the variability of the monthly rainfall, and the variability of rainfall in Australia is considerable (Delworth and Zeng, 2014), detecting significant trends at  $p < 5\%$  could be difficult. Therefore, an analysis based on  $p < 10\%$  is presented in the figures. At  $p = 10\%$ , 278 pixels in the QLD region had a significant positive  $Z'$  score, while 142 pixels in the NSW/VIC region were significant. In both cases this was a bit over 10% of the total area.

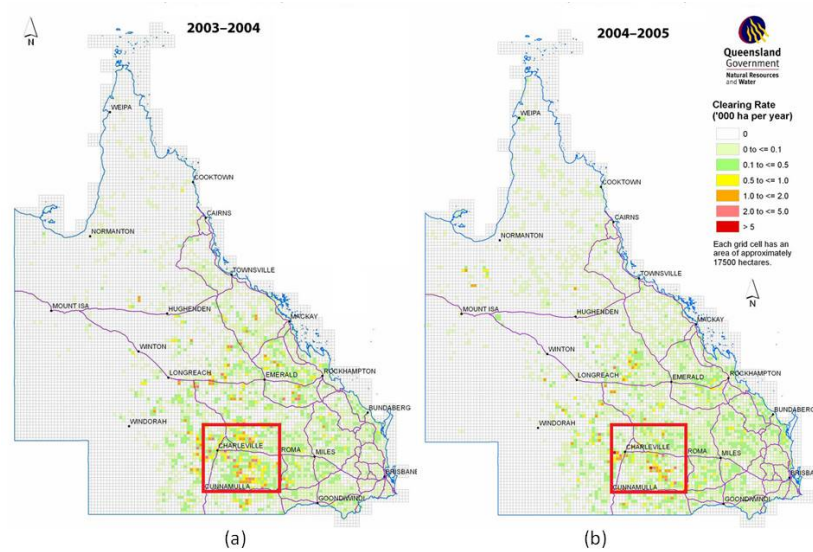


Figure 14: Woody vegetation clearing rate in QLD. The maps and figures are obtained from Department of Natural Resources and Water (2007). The red rectangle is the boundary of the QLD study region.

The rainfall residuals of the two periods (before-change since 1998 and after-change) were also compared (Figure 15). The annual values of the

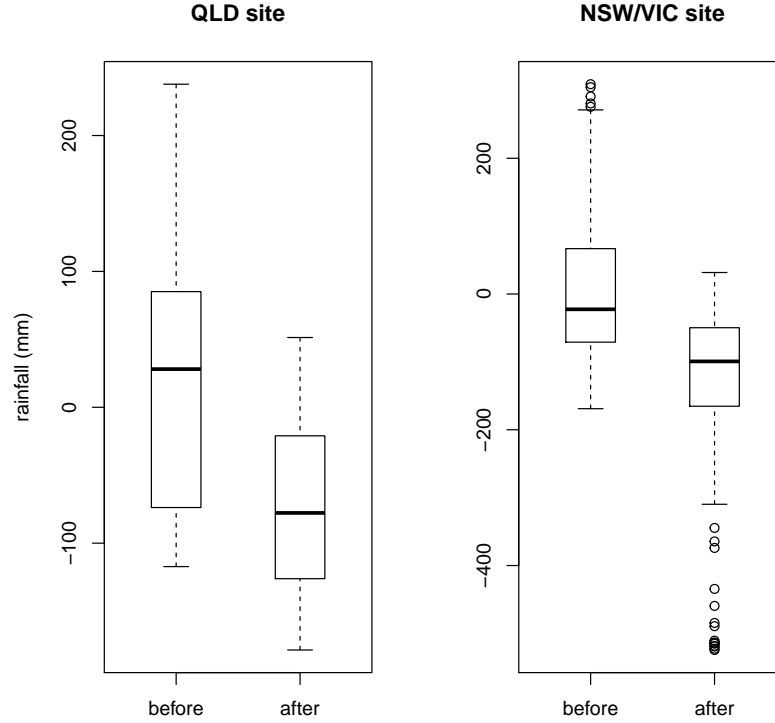


Figure 15: Boxplots of annual rainfall (estimated based on rainfall residuals from Equation 1) before and after the land cover intervention during 1998 - 2008 in the study regions. On average, the after period has a lower annual rainfall amount and with outliers of small values.

11-year period (1998 - 2008) were calculated for each pixel. The boxplots indicate that there were different mean values between the “before” and “after” periods in both regions. There are small outliers in the after period in NSW/VIC. A close look at the rainfall data revealed that rainfall was consistently very low in 2006 for the whole region. The low rainfall in 2006 was due to a weak El Niño and memory effects of the previous drought. While

552 the regression model has removed most of the effect of ENSO, the cumula-  
 553 tive drought effect could still be visible in the residuals if the response of  
 554 the rainfall to the ENSO effect is non-linear, and the memory of the past  
 555 drought is persistent. This can also explain the significant results in the pre-  
 556 vious method. To remove the outlier effects, the two periods were compared  
 557 excluding the 2006 rainfall. An F test confirmed that the variances were  
 558 different between the before and after periods. Hence an unpaired unequal  
 559 variance two sample t-test was applied to test whether the after period has  
 560 lower mean rainfall than the before period, for the group of pixels showing  
 561 a negative step change in rainfall ( $p = 0.05$ ) and the group of pixels with no  
 562 change. The rainfall in the after period was lower than the before period ( $p$   
 563  $< 0.05$ ) for pixels showing a negative step change. For those pixels without  
 564 a step change, there was no statistical evidence that the two periods have  
 565 different means. Hence the t-test results are consistent with the step trend  
 566 test results.

567 The choice of  $ns$  has some impact on the test results, as shown by Hirsch  
 568 and Gilroy (1985). The cases of  $ns = 1$  and  $ns = 9$  were also tested. When  
 569  $ns = 1$ , 18 pixels in the QLD region obtained a  $Z'$  score at the 5% significance  
 570 level. In the NSW/VIC region, the detection of negative step change ( $p =$   
 571  $0.05$ ) reduced to 16 pixels. On the other hand, when  $ns = 9$ , the results  
 572 were similar to the case of  $ns = 4$ . In this case, the changes ( $p = 0.05$ )  
 573 were detected in 35 pixels in the QLD region and 18 pixels in the NSW/VIC  
 574 region. The power of the test does not change much after  $ns = 4$ , as shown  
 575 by Hirsch and Gilroy (1985). The cause of the somewhat inconsistent results  
 576 in the QLD region between  $ns = 1$  and  $ns = 4$  is unclear. This could possibly

577 be because the higher  $ns$  values smooth the individual pixel results.

578 The "field significance" of the test is considered to make inferences about  
579 the step change at regional scales from multiple local tests (Wilks, 2006;  
580 Westra et al., 2013). Here, the bootstrapping resampling method from Wes-  
581 tra et al. (2013) was modified to evaluate the field significance. The spa-  
582 tial structure of the pixels was maintained, while the order of the years and  
583 months, were changed by random resampling. The test statistic identifies the  
584 percentage of the pixels with significant step change, positive and negative  
585 respectively, for the step trend test. The test statistics on 1000 resampled  
586 replicates were used to develop the distribution of these percentage values  
587 under the local null hypothesis that there was no step change.

588 The bootstrapping resampling technique was applied on both  $ns = 1$  and  
589  $ns = 4$  cases. In the  $ns = 4$  case, a spatial moving block bootstrapping  
590 was used, in which the change of time sequence within the  $2 \times 2$  block was  
591 consistent. The distribution of the test statistics is highly concentrated at  
592 zero with a skew to the right. In the outputs, negative step changes in the  
593 cases of  $ns = 1$  and  $ns = 4$ , the test statistics on the observed time series  
594 generally fall within the null hypothesis distribution (the cases of  $ns = 4$  are  
595 shown in Figure 16 and Figure 17). However, the bootstrap distribution is  
596 very wide and highly skewed, with step change values close to 0. The result  
597 for both the positive Queensland and positive NSW/VIC  $ns = 4$  step change  
598 tests are located much further to the right on the tail of the distribution,  
599 away from 0 and give a stronger indication of a change. The results showed  
600 that overall the chance of detecting a rainfall change was small, which is  
601 related to the strong natural variability of the rainfall in Australia. However,

602 the location of the positive tests on the tail of the distribution suggests some  
 603 support for the hypothesis that vegetation cover change affects local rainfall.

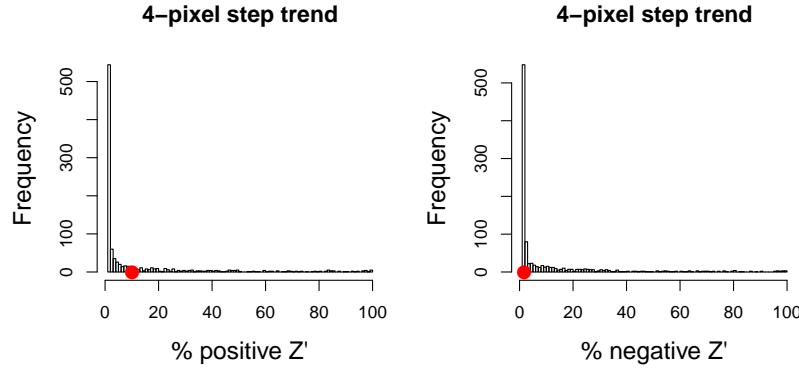


Figure 16: Percentage of pixels showing statistically significant positive  $Z'$  values (left) and negative  $Z'$  values (right) in QLD at  $p < 0.1$ . The histogram shows the distribution of results from 1000 bootstrap resampling of the rainfall time series. The red dot represents the results from the observed data.

## 604 6. Summary and Discussion

605 Generally, empirical studies on LCC-precipitation interaction are con-  
 606 ducted within an area with known land surface intervention (e.g. Otterman  
 607 et al., 1990; Durieux et al., 2003; Negri et al., 2004; Sato et al., 2007). How-  
 608 ever, these locations are rare and difficult to isolate from real landscape  
 609 change. In this study we therefore tested the effect of land cover change  
 610 across a broad region, rather than only for locations where changes were  
 611 known to occur or have occurred. The advantage of this approach is that it  
 612 does not require a long time series of land cover data which is usually un-  
 613 available. Furthermore, it does not assume a specific relationship between

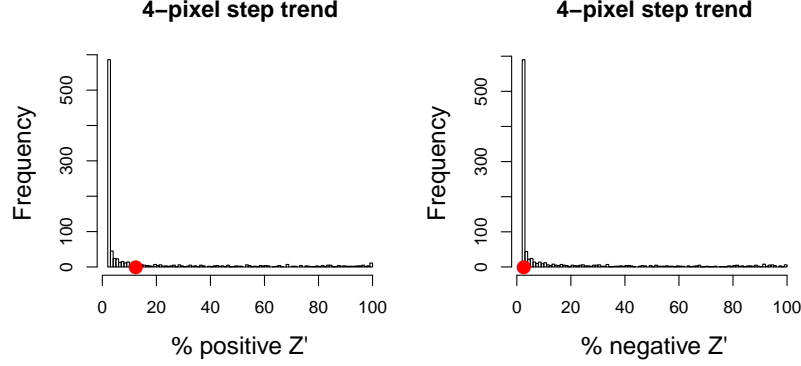


Figure 17: Percentage of pixels showing statistically significant positive  $Z'$  values (left) and negative  $Z'$  values (right) in NSW/VIC at  $p < 0.1$ . The histogram shows the distribution of results from 1000 bootstrap resampling of the rainfall time series. The red dot represents the results from the observed data.

614 vegetation cover change and rainfall but allows the data to show this rela-  
615 tionship, by applying the analysis to a broader area outside the boundary  
616 of the vegetation cover change. This approach is expected to provide a way  
617 to reduce the risk of a false positive paradox, by comparing results between  
618 areas with and without vegetation cover change.

619 Parametric tests are generally more powerful than nonparametric test in  
620 detecting a trend, when the data is normally distributed (Onoz and Bayazit,  
621 2003; Kundzewicz and Robson, 2004). As a non-parametric test, the step  
622 trend test has the advantages of distribution free and having no restriction  
623 on missing data (Hirsch and Gilroy, 1985). This is particularly useful in  
624 rainfall analysis since rainfall data is usually skewed. On the other hand, the  
625 disadvantages of non-parametric tests, such as being limited to hypothesis  
626 testing and weaker in power, also hold for the step trend test (Whitley and

627 Ball, 2002).

628 The regression model used here is a simple model. We only consider the  
629 important effects of historical trend, seasonality and climate drivers. Fur-  
630 thermore, no more than two large scale climatic indices were used in order to  
631 avoid over-parameterisation and multiple cross-correlations between climatic  
632 indices. A purpose of the regression model is to remove the variability in  
633 rainfall that is due to these known important factors. The model shows that  
634 seasonality, ENSO and IOD together explain no more than 20% of the rain-  
635 fall variability, and around 6 - 8% on average is due to the climate drivers.  
636 This is consistent with the literature (e.g. Westra and Sharma, 2010). A  
637 large amount of variation is left in the model residuals, which is likely due  
638 to random factors. Rainfall is generally considered a stochastic process (e.g.  
639 Fowler et al., 2005; Cowpertwait et al., 2009; Burton et al., 2010). The high  
640 variability increases the difficulty to detect a change in rainfall.

641 There was some evidence that a step change has occurred in the QLD  
642 region. The semi-parametric model could not identify any step change in the  
643 rainfall data. On the other hand, the step trend test suggested a couple of  
644 locations (300 - 500 km<sup>2</sup>) might have experienced rainfall change ( $p = 0.05$ ).  
645 The results from the step trend test also indicated a possible widespread  
646 change, but the spatial pattern of change is not consistent with the tree  
647 cover change map. Although land clearings in QLD have occurred at a high  
648 rate and broad scale (Department of Natural Resources and Water, 2008),  
649 this study cannot confirm its impact on the local rainfall. At this location,  
650 land cover change was not found to change the mean rainfall significantly in  
651 some other studies (e.g. Narisma and Pitman, 2003; McAlpine et al., 2007).

652 The characteristics of vegetation cover changes in QLD might increase the  
653 difficulty in detecting a step change. QLD has a long history of land clearing.  
654 According to the series of SLATS reports on land cover changes in QLD re-  
655 leased by the Queensland government, land clearing continued in and around  
656 the study region between 1988 - 2008. Major broad scale and high rate clear-  
657 ings occurred in 1999 - 2000 and 2002 - 2004. It is therefore difficult to define  
658 a clear cut change in this region. The more continuous ongoing land clear-  
659 ing could have reduced the significance of a step change. The two methods  
660 indicate quite different results on the level of change in the NSW/VIC re-  
661 gion. The semi-parametric model showed that a large area in the NSW/VIC  
662 region has experienced significant step change ( $p = 0.05$ ) in rainfall after  
663 2003. But this result is likely to be affected by the low rainfall in 2006 as  
664 the area is larger than the bushfires region. The step trend test was able to  
665 detect significant changes ( $p = 0.05$ ) in about 400 km<sup>2</sup> areas in the Snowy  
666 Mt. and some possible changes along the bushfires region ( $p = 0.1$ ). This  
667 might be due to the possible small size of the step change and/or a short  
668 after-fire period (Hirsch and Gilroy, 1985). The vegetation cover change due  
669 to bushfires might have possibly changed the rainfall but the evidence was  
670 not strong either.

671 The bushfires locations highlighted in the analysis results is an interesting  
672 outcome. The results might be due to a drought effect. The 2002 - 2003  
673 drought has affected rainfall in a large part of Australia, particularly the  
674 MDB (Nicholls, 2004). The severe bushfires in 2003 were also triggered by  
675 the extreme drought conditions. Although the dry episode effect on rainfall  
676 has been accounted for in part by the SOI, further impact of drought could be



677 passed through the local land-atmosphere interaction. However, this impact  
678 might not be statistically significant, even under an extreme event such as  
679 bushfires. Overall, the rainfall feedback to the vegetation cover change could  
680 be weak under dry conditions.

681 The different causes of vegetation cover change in these two regions could  
682 lead to different post-change characteristics. The magnitude of EVI decreasing  
683 trends in the QLD region are less than in NSW region, as reported in the  
684 DLCD data. This is due to the lower tree density in the QLD region than  
685 in the NSW/VIC region before land surface interventions. Wild fires might  
686 have totally damaged the vegetation cover and recovery was very slow in some  
687 areas within the Snowy Mt. The persistent drought in the 2000s (Howden,  
688 2012) has delayed the regrowth of trees. On the other hand, replacing tree  
689 cover with pasture and crops might have a relatively subtle impact on the  
690 EVI. On the other hand, regrowth of trees can be expected after fires or as  
691 drought condition is relieved; but clearings for agricultural purpose impose  
692 permanent or semi-permanent changes to the land surface.

693 The rainfall data used in this study is a gridded data set. This data  
694 set is robust and consistent over a long time series (from 1900 to current)  
695 and has a broad national wide coverage which can provide more information  
696 spatially. However, high cross correlation between pixels due to the interpolation  
697 method generating this data set can also introduce spatial noise. Here  
698 the cross correlation has been account for in the step trend test. Some other  
699 methods are also available which can be used to perform a comparative trial.  
700 For example, Narisma et al. (2007) applied a spatial Gaussian filter on a similar  
701 data set and used wavelet analysis to detect step change in rainfall. High

quality station data is another option to test whether the observed spatial pattern in the step trend test results was not due to the gridded data itself. Resampling methods, such as bootstrapping and permutation (Wilks, 1997; Kundzewicz and Robson, 2004; Westra et al., 2013), can also be used to further assess the strength of significance of results and incorporate spatial and temporal patterns in the analysis. We are also aware that the gridded data set is most useful in regions with sparse rain gauge networks but it actually reduces information where the rain gauge density is high (Jones et al., 2009). In the Snowy Mountains area, the coverage of rainfall stations is intensive but they are mainly located in the valleys. The interpolated data might not best represent the local rainfall.

Overall, the inclusion of the anomalous rainfall year 2006, could have influenced the results, and this means that strong conclusions cannot be drawn.

However, the current study provides some evidence to reject the null hypothesis (no step change in rainfall is due to the tree cover loss). Limited by the available data, the time frame under study was chosen within a long lasting drought period (Holper, 2011). The strong impact of this prolonged drought might have suppressed the land-atmosphere interaction and confused the cause and effect relation between rainfall and vegetation cover change. This could be one of the reasons that the LCC effects found in other studies (Görgen et al., 2006; McAlpine et al., 2007, e.g.) are not found to be significant here. So possible future work can be conducted for a non-drought period, when a longer series of land cover data is available. This approach should be further assessed in different scenarios of wet period and/or af-

727 forestation. Continuous monitoring of land surface conditions is important  
728 for future research. The power of the test can also be improved with the  
729 longer length of the after-intervention period (Hirsch and Gilroy, 1985). But  
730 then the question is what is an appropriate length for land cover change  
731 study, when ongoing change is possible, such as tree regrowth or cropping.  
732 This will require further research.

## 733 **7. Conclusion**

734 In this study, we found some observationl data based evidence, although  
735 not strong, that vegetation cover change has changed local rainfall. The  
736 semi-parametric method and non-parametric method did totally agree on  
737 detecting a significant step change in rainfall in the hot dry QLD region  
738 where land clearing has occurred. On the other hand, the bushfires in the  
739 humid, temperate mountain range in the NSW/VIC region has experienced  
740 reduced rainfall. But the dry spell also plays an important role in the results.

741 Drought has had a pronounced impact on the land surface condition dur-  
742 ing the study period, leading to significant reduction in vegetation and ex-  
743 treme events such as bushfires. The associated lack of rainfall and high  
744 temperatures may mask the step change in the vegetation. Hence, the sig-  
745 nal of LCC feedback on rainfall is probably weaker under such regional dry  
746 conditions, as the impact of LCC on rainfall is mainly through changes in  
747 moisture convergence (Görger et al., 2006; Pitman and Hesse, 2007).

## 748 **8. acknowledgments**

749 CL was supported by an Australian Postgraduate Award for this work.

750 **Appendix A. Summary of Data**

Table A.2: Summary of data.

Data	Source	Resolution		Analysis period
		Temporal	Spatial	
Percent tree cover	MOD44B	Annual	250m	2000-2010
Trend of vegetation cover change	DLCD (2009)	Onetime	250m	Trend of Apr 2000 - Apr 2008
Rainfall	AWAP gridded rainfall data	Monthly	$0.05^{\circ} \times 0.05^{\circ}$	Jan 1979- Dec 2008
SOI	BoM	Monthly	N/A	Jan 1979- Dec 2008
NINO 3, 3.4, 4	IRI/LDEO data library	Monthly	N/A	Jan 1979- Dec 2008
PDO	NOAA	Monthly	N/A	Jan 1979- Dec 2008
IOD	POAMA-2 dataset	Monthly	N/A	Jan 1979- Dec 2008

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