On the non-stationarity of hydrological response in anthropogenically unaffected catchments: An Australian perspective

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Introduction

The supplementary material includes three sections. Section 1 describes the methodology for detecting changes in precipitation seasonality based on the seasonality index and precipitation percentiles between 1984-1996 and 1997-2009 sub-periods. Section 2 describes properties of two remotely sensed vegetation products for exploring annual precipitation-productivity relationships.

Figure S1 shows distribution of water- and energy- limited catchments according to the Budyko framework. In Figure S2 normalized sensitivities of fractional vegetation cover to precipitation for two sub-periods (1984-1996 and 1997-2009) are presented.

Table S1 has the percentages of tree and grass land cover types in non-stationary catchments. Table S2 and S3 have the results of precipitation seasonality and Spearman rank correlations for catchment classification respectively. Table S4 has the properties of remotely sensed vegetation products.

1 Changes in precipitation seasonality

To detect changes in the precipitation seasonality between the two sub-periods (1984-1996 and 1997-2009), the bootstrapping approach of Pryor and Schoof (2008) is implemented. It should be noted that the 1997-2009 period corresponds to the millennium drought in Australia (Chiew et al., 2014). For every catchment, 1000 realizations of the mean seasonality index (SI) values during 1997-2009 were generated and 99% confidence intervals are calculated from the samples. Next, the mean SI values of the 1984-1996 period are compared against the sampling confidence interval to determine the significance of changes in the SI values between the two sub-periods. Results indicate that there has not been a significant intensification of precipitation seasonality across the non-stationary catchments except for two catchments in group A1 (Table S2). To detect a shift in the timing of precipitation between the two sub-periods, the bootstrapping approach is implemented across the precipitation percentiles of non-stationary catchments. Results indicate that all catchments present significant shifts in timing of the percentile day of the year where the total annual precipitations are reached except in catchments 318076 and G8110004. These shifts are particularly evident for the 25th and 10th percentiles among the non-stationary catchments (Table S2).

2 Remotely sensed vegetation products

Two additional remote sensing vegetation products, Enhanced vegetation index (EVI) (Huete et al., 2002, 2006), and Vegetation Optical Depth (VOD) (Liu et al., 2011), are used to assess annual precipitation-productivity relationships at the catchment scale. The Australia coverage of despiked EVI dataset (2001-2010) from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD13Q1 product are obtained from Geoscience Australia. The EVI 16 day product has a spatial resolution of 250m and is more sensitive to net primary productivity compared to normalized difference vegetation index (NDVI) (Huete et al., 2002, 2006).

Global long-term VOD dataset (1988-2010) from passive microwave satellites with 0.25º spatial resolution are obtained from Liu et al. (2011). VOD is related to water content of leaf and woody components of aboveground biomass (Liu et al., 2015). Compared to NDVI, VOD is able to detect structural differences in areas with near-closed canopy.

Because MODIS EVI is only available for smaller time period than the AVHRR F_{tot} dataset, only Spearman rank correlations between MODIS EVI and fractional vegetation cover is established for individual catchments. Results indicate significant correlations in most catchments (Table S4). For the VOD, correlations with annual precipitation and F_{tot} dataset are explored. As shown in Table S4, VOD dataset provide a similar grouping of non-stationary catchments except for one catchment in class A1 and three catchments in class B. In these three catchments in class B, correlation coefficient between annual precipitation and VOD is quite small.
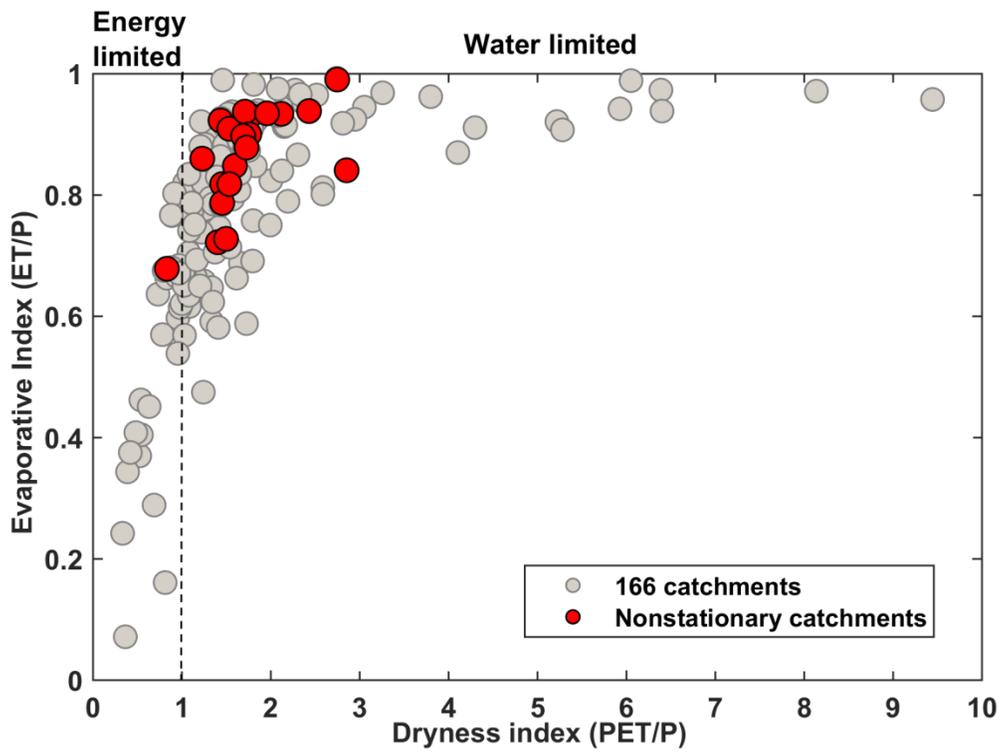
Figure S1: Distribution of water- and energy- limited catchments according to the Budyko framework using data from 166 Hydrologic Reference Stations (HRS) across Australia (1984-2010). Red circles show non-stationary catchments. The North Esk catchment (318076) in Tasmania is the only energy-limited non-stationary catchment.
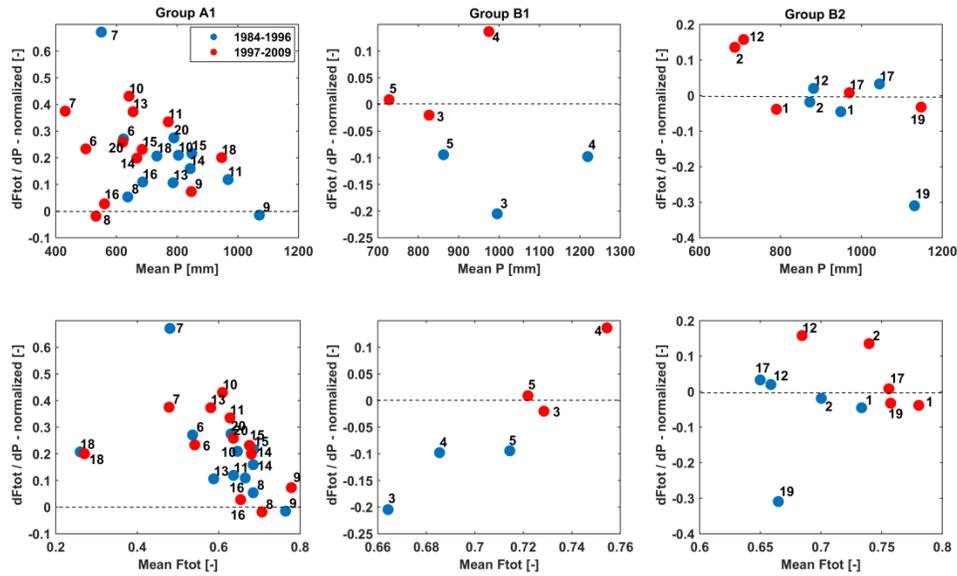
Figure S2: Normalized sensitivities of annual fractional vegetation cover (F_{tot}) to annual precipitation (P) in relation to mean annual precipitation (top) and mean annual fractional vegetation cover (bottom) across three classes of non-stationary catchments for two sub-periods: 1984-1996 and 1997-2009. For catchment identification numbers refer to Table 1.

As can be seen in Figure S2, changes in the magnitudes and directions of normalized sensitivities of B1 and B2 catchments correspond to increases in fractional vegetation cover during the drier period (1997-2009). Perhaps increases in nutrient availability are the cause of the vegetation increase. In group A1 catchments, changes in the direction of slopes are only observed in catchments 8 and 9. In catchment 9, the largest difference in mean annual precipitation between the two sub-periods is observed (224 mm) which is the likely cause of the observed trend. Similar patterns are observed in catchments 12 and 17. Catchment 12 has the smallest fractional vegetation cover in the B2 class (Table 1) and the fractional vegetation cover sensitivity to precipitation is increased in 1997-2009 period due to 173 mm decline in precipitation. Catchment 17 has the largest difference in fractional vegetation cover between the two sub-periods (0.11) which decreases F_{tot} sensitivity to precipitation.

Table S1: Non-stationary catchments in Australia. Percentages of grass and tree in each catchment are obtained from the National Dynamic Land Cover (NDLC) data set of Australia (Lymburner et al., 2010). Class refers to catchment classification framework presented in Figure 5.

Station	Catchment Name	NDLC		Class
		%Grass	%Tree	
406214	Axe Creek at Longlea, VIC	29.1	70.9	A1
408200	Avoca River at Coonooer, VIC	52.8	47.2	A1
408202	Avoca River at Amphitheatre, VIC	47.8	52.2	A1
410061	Adelong Creek at Batlow Road, NSW	31.1	68.9	A1
410705	Molonglo River at Burbong, ACT NSW	17.1	82.9	A1
410731	Gudgenby River at Tennent, ACT	4.8	95.2	A1
410761	Murrumbidgee River below Lobbs Hole Creek, ACT/NSW	11.9	88.1	A1
412028	Abercrombie River at Abercrombie, NSW	30.7	69.3	A1
412066	Abercrombie River at Hadley No.2, NSW	35.0	65.0	A1
415207	Wimmera River at Eversley, VIC	33.3	66.7	A1
G8110004	East Baines River at Victoria Highway, NT	3.1	96.9	A1
405238	Mollison Creek at Pyalong, VIC	60.2	39.8	A1
215004	Corang River at Hockeys, NSW	1.0	99.0	B1
216004	Currambene Creek at Falls Creek, NSW	1.0	99.0	B1
218001	Tuross River at Tuross Vale, NSW	2.6	97.4	B1
212260	Kowmung River at Cedar Ford, NSW	7.6	92.4	B2
215002	Shoalhaven River at Warri, NSW	27.1	72.9	B2
410734	Queanbeyan River at Tinderry, ACT	15.6	84.4	B2
613146	Clarke Brook at Hillview Farm, WA	11.3	88.7	B2
318076	North Esk, TAS	9.8	90.2	B2

Table S2: Mean precipitation seasonality index of each non-stationary catchment for the 1984-2010, 1984-1996 and 1997-2009 periods. Mean differences in the day of a year where 10th, 25th, 50th, 75th and 90th percentiles of the annual precipitation are reached between the two sub-periods (1984-1996 and 1997-2009). Positive values indicate later onset of the percentile values relative to the 1997-2009 period.

Station	SI (1984-2010)	Mean SI (1984-1996)	Mean SI (1997-2009)	Mean differences in the day of a year between the decades				
				10th	25th	50th	75th	90th
212260	0.49	0.49	0.49	27*	13	103*	-2	13
215002	0.57	0.57	0.56	21*	-55*	14	39	39
410734	0.55	0.56	0.53	-2	-13	-37	108*	34
613146	0.77	0.75	0.79	3	11*	-37*	11	-27
318076	0.47	0.45	0.5	13	-8	28	-9	5
215004	0.57	0.57	0.57	1	-35*	85*	29	-9
216004	0.58	0.6	0.56	7	8	-62	83*	-57
218001	0.61	0.61	0.59	8*	18*	1	64	64
406214	0.54	0.58	0.51*	2	11	-24	-4*	-26
408200	0.55	0.6	0.52*	10*	54*	-7	25	0
408202	0.50	0.52	0.49	4	50*	-40	42	-49
410061	0.52	0.53	0.52	3	21*	-20	-34	-28
410705	0.53	0.54	0.53	6	14*	19	8	82
410731	0.49	0.5	0.49	11*	98*	-11	-11	41
410761	0.49	0.49	0.47	46	-7	29	60	1
412028	0.46	0.46	0.45	52*	-77*	15	65*	53
412066	0.46	0.46	0.46	47*	-5	-17	16	-4
415207	0.51	0.53	0.49	4	65*	-27	4	0
G8110004	1.1	1.08	1.12	-1	0	-2	-8	-57
405238	0.53	0.56	0.51	5*	39*	-71	7	-47

*The difference in mean SI or the percentile values of the two sub-periods is significant at α=0.01%.

Table S3: Spearman rank correlations between annual precipitation and mean annual temperature (r_1), and fractional vegetation cover with mean annual temperature (r_2), and mean annual sunshine hours[1] (r_3) for non-stationary catchments in Australia (1984-2010). Class categories refer to the catchment classification framework of Figure 5.

Station	r_1	r_2	r_3	Class
406214	-0.32	-0.16	-0.09	A1
408200	-0.28	-0.19	-0.26	A1
408202	-0.30	-0.14	-0.21	A1
410061	-0.58*	-0.10	0.18	A1
410705	-0.18	-0.26	-0.46*	A1
410731	-0.24	-0.14	-0.13	A1
410761	-0.06	-0.02	-0.19	A1
412028	-0.53*	-0.25	-0.47*	A1
412066	-0.43*	-0.24	-0.52*	A1
415207	-0.33	-0.31	-0.31	A1
G8110004	-0.54*	-0.57*	-0.09	A1
405238	-0.20	-0.08	-0.10	A1
215004	0.03	0.11	0.50*	B1
216004	-0.10	0.13	-0.21	B1
218001	0.15	0.00	0.14	B1
212260	-0.32	0.19	-0.13	B2
215002	-0.09	0.01	0.04	B2
410734	-0.06	-0.06	-0.01	B2
613146	-0.01	0.16	0.08	B2
318076	0.18	0.14	0.07	B2

*Correlation is significant ($p < 0.05$)

[1]Sunshine hour data are obtained from seven meteorological stations that are closest to the non-stationary catchments and have the most number of data records for duration of the analysis (1984-2010).

Table S4: Spearman rank correlations between annual VOD and annual fractional cover (F_{tot}) from AVHRR (r_1), annual VOD and annual precipitation (r_2), and annual EVI and F_{tot} (r_3), in non-stationary catchments.

Station	r_1 (1988-2010)	r_2 (1988-2010)	r_3 (2001-2010)	Class
406214	0.44*	0.48*	0.72*	A1
408200	0.36	0.50*	0.94*	A1
408202	0.63*	0.50*	0.21	A1
410061	0.62*	0.08	0.79*	A1
410705	0.63*	0.30	0.95*	A1
410731	0.82*	0.28	0.98*	A1
410761	0.69*	0.17	0.95*	A1
412028	0.46*	0.07	0.85*	A1
412066	0.36	-0.12	0.84*	A1
415207	0.58*	0.48*	0.60	A1
G8110004	0.40	0.66*	0.27	A1
405238	0.53*	0.38	0.89*	A1
215004	0.47*	-0.02	0.44	B1
216004	0.63*	-0.42	0.82*	B1
218001	0.41	-0.04	0.82*	B1
212260	0.20	0.06	0.62	B2
215002	0.49*	-0.19	0.92*	B2
410734	0.54*	0.15	0.73*	B2
613146	0.54*	-0.43*	0.38	B2
318076	0.65*	-0.01	0.61	B2

*Correlation is significant ($p < 0.05$)