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Rainfall Variability in the Shoalhaven River Catchment and its Relation to Climatic Indices

Rafael C. Carvalho[1] · Colin D. Woodroffe[1]

Abstract The management of the Shoalhaven River, in southern Australia, is important for water supply and floodplain issues including flooding and acid sulphate soil management. Analysis of the spatial variation in rainfall was performed in order to assess temporal and geographical variability within this east Australian catchment and its relationship to large-scale climate drivers, such as the Southern Oscillation Index (SOI), the Interdecadal Pacific Oscillation (IPO), particularly in its negative phase, and the Atmospheric Blocking Index. A total of 141 rain gauges located within a 10-km buffer around the perimeter of the Shoalhaven catchment provided rainfall information spanning from 1885 to 2011. The highest annual mean was in 1950 (1670 mm), with other wet years in 1959 (1564 mm) and 1974 (1571 mm), and the lowest mean was in 1982 (440 mm) and 1944 (446 mm). In the calendar year of 2011 (922 mm), March accounted for 14.5 % of the annual rainfall while April, May and September accounted for less than 5 %. Interpolation between rainfall gauges indicated that the highest rainfall areas occurred in the lower catchment, adjacent to the coast, where there is a pronounced orographic effect. Although it has been implied that drought in this region is related to El Niño years, there was only a weak positive correlation between catchment rainfall and SOI which was moderately enhanced during negative phases of IPO. Seasonal influence of Atmospheric Blocking could be detected on the rain-gauge records during April–October. These findings provide insights not only for this catchment but also for other parts of southeast Australia, implying that coastal catchments may not have strong linkages to key climatic drivers as previously inferred, and management actions and planning on the basis of these climatic indices are not recommended.

Keywords Rainfall variability · Spatial interpolation · ENSO · IPO · Atmosphere blocking · Shoalhaven River

✉ Rafael C. Carvalho
  rcc919@uowmail.edu.au

[1] School of Earth and Environmental Sciences, University of Wollongong, Wollongong NSW 2522, Australia

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1 Introduction

Precipitation is regarded as the most important input into a hydrological system and its accurate assessment is fundamental to effective water resource management (Mohssen et al. 2011). Measured precipitation in catchments is useful in a variety of hydrological applications (Black 1996). It provides the basis for flood assessments, and may be used to estimate sediment delivery, determine navigation potential, or calculate water supply to humans, livestock, irrigation requirements and energy demands. Understanding the influence of climate drivers and their hydrologic relationships can aid water management decision making by providing a lead-time of months to mitigate drought or flood impacts (Abtew and Trimble 2010; Misir et al. 2013).Technical and financial limitations hinder our understanding of precipitation distribution in time and space. Spatial distribution depends upon latitude, orographic factors, continentality, prevailing wind directions and the distance an air mass moves away from the source of moisture (Naoum and Tsanis 2003). Pronounced seasonal variation occurs where the annual circulation changes the amount of moisture inflow at regional scales (Chow et al. 1988).

The Shoalhaven River is 340 km long and drains the largest catchment (7151 km^2) in southern New South Wales, southeast Australia (Fig. 1). Most of the catchment (upstream from Tallowa Dam) is managed by the Sydney Catchment Authority as part of the scheme to transfer water to supply 4.5 million people living in Australia's largest city. The river rises in the Great Dividing Range; its upper reaches are in the Paleozoic Lachlan Fold Belt, whereas the middle and lower reaches lie within the near-horizontally bedded Permo-Triassic southern parts of the Sydney Basin. The river has largely infilled a Holocene deltaic-estuarine plain east of Nowra, which is intermittently subjected to flood events. During dry periods, the impact of
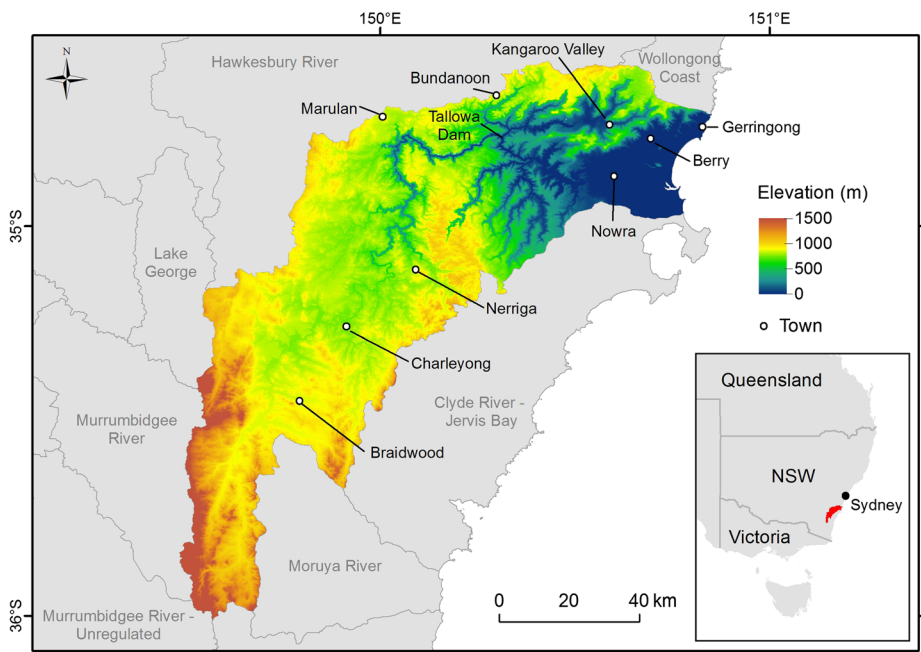
Fig. 1 Elevation of the Shoalhaven catchment and location of adjacent river basins

past flood drainage practices on iron sulfide mineral sediments acidifies water killing aquatic life and corroding exposed infrastructure (Healthy Rivers Commission of NSW 1999). The catchment vegetation has been partially cleared. Native eucalypt forests covered approximately 50 % of the area in 1980, with half of the forest occurring on steep slopes. Approximately 30 % of the catchment was natural pasture and 15 % was under improved pasture. Intensive agriculture occupied ~2 % of the catchment area (Aston and Dunin 1980).

Climatic variability in coastal NSW has been previously identified over a range of spatial and temporal scales. Average annual rainfall along the coast of NSW ranges from about 850 mm in the south to about 1700 mm in the north, with no dramatic seasonal changes, despite a marked difference in seasonal and geographical distribution, caused by movement of atmospheric pressure systems (Chapman et al. 1982; Cordery and Opoku-Ankomah 1994).

Rainfall occurs along the coast, associated with moisture-bearing southerly air streams, with orographic rainfall along the escarpment to the north. Rainfall reliability also decreases from the coast inland. The coastal mountain range experiences high rainfall variability and is vulnerable to heavy-rain producing systems such as tropical and mid-latitude cyclones (Sinclair 1994).

Although the influence of variations in the El Niño-Southern Oscillation (ENSO), expressed as the South Oscillation Index (SOI), on rainfall in Australia is well documented (McBride and Nicholls 1983; Ropelewski and Halpert 1987; Allan 1988; Drosdowsky 1993; Power et al. 1998; Kiem and Franks 2001; Verdon-Kidd and Kiem 2009), Chiew et al. (1998) suggested that this correlation is not sufficiently strong to predict rainfall accurately. McBride and Nicholls (1983) pointed to the existence of a distinct seasonal cycle in this correlation, with the best (worst) relationship occurring in spring (summer). Nicholls and Kariko (1993) suggested that SOI affects rainfall in eastern Australia mainly by influencing the number and intensity of rain events. Furthermore, the influence of La Niña on rainfall tends to be greater for northern NSW and Queensland, and weaker for Victoria (Verdon et al. 2004). In NSW, linkages between SOI and rainfall have been found to have changed with time and regionally within the state (Opoku-Ankomah and Cordery 1993).

The Interdecadal Pacific Oscillation (IPO) is a climate phenomenon that mediates the influence of ENSO. An IPO index has been developed that captures multidecadal Sea Surface Temperature anomalies through the use of a 13-year cut-off lowpass filter. During IPO negative phases, a further magnification of rainfall during La Niña events is recognised (Power et al. 1999; Verdon et al. 2004).

The pattern of variation of ENSO itself has also changed over time (Torrence and Compo 1998), as have other influential large-scale circulation systems. Long-term changes in the spatial and temporal characteristics of rainfall are a consequence of the changes in the systems causing rainfall (Kirkup et al. 2001). El Niño events disrupt the location of the South Pacific Convergence Zone (SPCZ), preventing its propagation to its usual southern latitude, whereas La Niña events propagate the SPCZ further south delivering more frequent rainfall across southeast Australia (Salinger et al. 1995). Teleconnections with climate drivers from the Indian Ocean (the Indian Ocean Dipole, IOD) and the Southern Ocean (Southern Annular Mode, SAM) have been inferred (Ummenhofer et al. 2009), although the effects of these are difficult to detect, and are disputed (Cai and Cowan 2013).

Atmospheric blocking is another important climate driver which influences rainfall across the southern half of the continent. It occurs when a high-pressure system remains almost stationary and blocks the easterly progression of weather systems across southern Australia and into the Tasman Sea (Risbey et al. 2009). Low-pressure systems are either diverted south, or some cutoff lows may divert north of the high-pressure system, enhancing rainfall.

This study aims to examine temporal and spatial variability of rainfall within the catchment by interpolating rain gauge record time-series data for annual and monthly (2011 calendar year) rainfall and assess the extent to which rainfall IDW the Shoalhaven catchment is explained by the SOI and related climate drivers, in order to provide guidance as to their likely predictive capacity to assist water supply and floodplain management.

2 Materials and Methods

The Climate Data Online website (http://www.bom.gov.au/climate/data/) of the Bureau of Meteorology provides data and locations of rain gauges in Australia. Using the Australian Surface Water Management Areas 2000 dataset downloaded from Geoscience Australia website (http://www.ga.gov.au/), it was possible to select the 107 rain gauges located within the Shoalhaven catchment and in a GIS perform a 10 km buffer to identify another 66 stations located in adjoining catchments (Wollongong Coast, Hawkesbury River, rivers draining to Lake George, Murrumbidgee River, Moruya (Deua) River, and Clyde River and Jervis Bay basins. Thirty two out of the 173 rain gauges were discarded because they either had no data, not controlled data or missing data during some months. In the end, 141 rain gauges in total (86 within the Shoalhaven catchment and 55 in the adjacent basins) were used in this work. Beside this, four long-record rain gauges: 68003 ($n=1483$; Jul/1886–Dec/2011), 69010 ($n=$ 1487; Dec/1887–Dec/2011), 70012 ($n=1420$; Jan/1885–Dec/2011) and 70057 ($n=1332$; Mar/1898/Dec2011) were selected for monthly analysis, as well as lag correlation between SOI and rainfall in the following (1–12) months. These rain gauges registered the highest time-span data with minimum gaps in the time-series and also provided spatial representation for the lower, middle and upper catchment (Fig. 2). The calendar year of 2011 was chosen for monthly interpolation because of its similarity to the annual mean of 900 mm. For this task, 33 rain gauges (24 in the Shoalhaven catchment and 9 in the adjacent basins) were used. Unfortunately, none of the 141 rain gauges herein employed was listed in the Lavery et al. (1997) final dataset of 379 high-quality rainfall records for Australia.

After inputting the data into the GIS, the Inverse Distance Weighted (IDW) interpolation was performed. The IDW interpolation method determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance and the surface being interpolated should be that of a locationally dependent variable. This method assumes that the variable being mapped decreases in influence with distance from its sampled location (Philip and Watson 1982; Watson and Philip 1985). After interpolation, the Shoalhaven catchment was extracted using a mask of the watershed.

Despite no agreement existence about how best to portray variability between rain gauges. The arithmetic average presented here is the simplest and often the least accurate method of calculating mean precipitation (Black 1996). There have been many comparisons of rainfall interpolation methods, and there are no clear conclusions about which method might be best, partly because there is not enough observational data to say what the 'right' answer might be (Shaw et al. 2011). Hutchinson (1995) chose thin plate smoothing splines, Garcia et al. (2008) pointed out that the commonly used inversed square distance weighting was inferior to multi-quadric interpolation. Buytaert et al. (2006) found kriging more accurate for daily rainfall than Thiessen polygons. Creutin and Obled (1982) preferred Gandin's optimal interpolation (1965), Basistha et al. (2008) preferred universal kriging followed by ordinary kriging and IDW, while Ly et al. (2011) concluded that ordinary kriging and IDW were the best methods. On the other
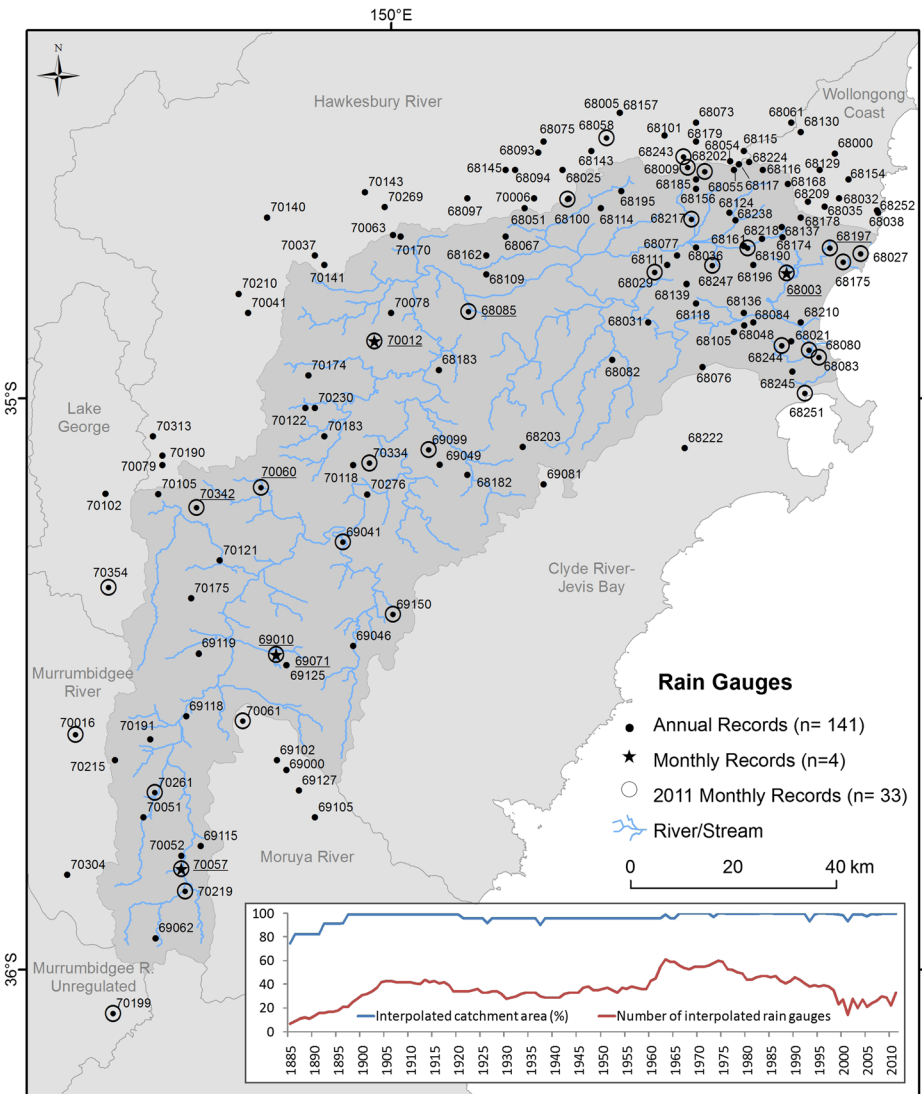
Fig. 2 Location of rainfall gauges. Underlined ones are referred in the text. Insert graph indicates the number of interpolated rain gauges (*red line*) and the percentage of the catchment area interpolated (*blue line*) between 1885 and 2011

hand, Dirks et al. (1998) suggested that kriging has no clear advantage over other methods, while Nalder and Wein (1998) found that the estimates with IDW had smaller errors than ordinary or universal kriging.

Figure 2 also shows the number of interpolated stations and the percentage of the catchment covered by each annual interpolation. The number of rain gauges used in the annual interpolation was only less than 30 in 32 years, or 25.2 % of the analysed time series. 47 years (1904–1917 and 1960–1992) used >40 stations, and 17 years between 1962 and 1978 used >50 stations. These figures are in accordance with the minimum density of stations proposed by the

WMO guidelines (2008) for coastal (900 km²/station) and mountain (250 km²/station) areas. Figure 2 also indicates that one of the strengths of this study is that 94.5 % of the annual time series (120 years) covered more than 90 % of the catchment area, 87.4 % (111 years) encompassed 95 % of it, and 52 % (66 years) encompassed more than 99 % of the Shoalhaven catchment. Only the early years of the record didn't account for information south of Braidwood, while it lacked information on the southwestern part of the catchment in 1937, 1993 and 2001. The wettest past of the basin, the lower catchment near the coast, was well represented in the interpolation in almost all years except 1885, and to a lesser degree in 2005. Consideration of the altitude of the gauge and the effect of orographic influences on rainfall were not specifically incorporated into the interpolations, although it can be inferred that the topography is important in explaining variation across the catchment, especially in the upper and middle catchment.

There are two sets of updated Australia-wide monthly 0.05° × 0.05° gridded rainfall data. However, during the course of this work, the Australian Water Availability Project (AWAP) dataset (Jones et al. 2009) had its distribution temporarily suspended due to important bias correction affecting the model results, while the SILO dataset (Jeffrey et al. 2001) was not accessed due to the associated costs. In any case, there is no simple way of assessing how accurately these gridded datasets capture the rainfall in ungauged areas (Tozer et al. 2011).

The influence of climatic indices on rainfall was assessed by using SOI, distinguishing IPO phases and considering Atmosphere Blocking. There are different methods to calculate SOI. This study used the Troup SOI, which is the standardised anomaly of the mean sea-level pressure difference between Tahiti and Darwin, computed on a monthly basis (Troup 1965) and used by the Australian Bureau of Meteorology. Sustained negative values below -8 indicate El Niño episodes whereas positive values above +8 are typical of La Niña episodes.

The negative phase of IPO considered here, happened between 1946 and 1976, excluding 10 years from 1958 to 1967, when the absolute value of the IPO index was less than 0.5 (Power et al. 1999).

The Atmospheric Blocking index used was developed by the Bureau of Meteorology for use in the Australian region (Pook and Gibson 1999) to calculate a monthly blocking index at 150°E, with wind data taken from the National Center for Environmental Prediction- National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al. 1996).

3 Results

3.1 Annual Variability

The average annual mean for the 1885–2011 time-series is 899.6 mm for the Shoalhaven catchment. The highest mean for any year happened in 1950 (Fig. 3), when 1970 mm, more than twice the average, fell; other years with high rainfall include 1959 (1564 mm), 1974 (1571 mm) and 1961 (1521 mm). Average rainfall in the catchment exceeded 1400 mm mark also in 1978 (1478 mm), 1956 (1435 mm), 1891 (1417 mm) and 1952 (1407 mm). The lowest mean occurred in 1982 (440 mm), a drought year with a pronounced El Niño, culminating in the Ash Wednesday bushfires in Victoria in February 1983. Low rainfall was also observed in 1944 (446 mm), 1888 (499 mm), 1980 (523 mm), 1965 (540 mm), 1940 (542 mm), 1968 (556 mm), 1907 (570 mm) and 1941 (590 mm). The interpolated rainfall maps for the catchment for many of these years are presented in Fig. 4.
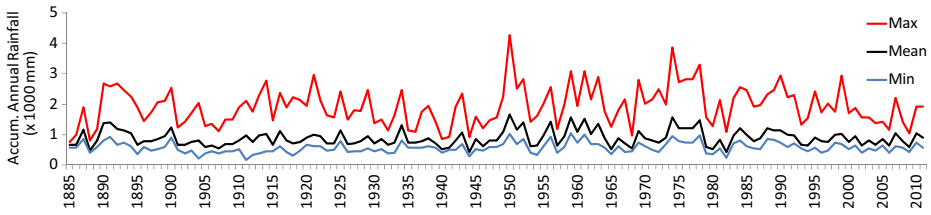
**Fig. 3** Mean, maximum and minimum rain gauge record for the Shoalhaven catchment from 1885 to 2011.

As expected, the highest rainfall areas occurred near the coast in the lower catchment. Worth noticing is the fact that during the years with highest rainfall, the coastal northeastern part of the catchment received 2-3 times as much rain when compared to the middle or upper parts. The highest annual recording by a single rain gauge was registered in the foothills just north of Berry at 68197 (4263.4 mm) in 1950, followed by stations 68168 (3854.6 mm), 68178 (3754.5 mm) and 38174 (3363.9 mm) in 1974, 68021 (3331 mm) in 1950, and 68168 (3308.5 mm) in 1978. Rainfall exceeding 2500 mm was recorded in eleven rain gauges for the calendar year of 1950, two gauges in 1959, twelve gauges in 1974, seven in 1978 and one in 1999.

Figure 5 depicts the rainfall variation around the mean annual rainfall. In the first half of last century a dry period occurred and rainfall variation was below the mean annual rainfall more than 200 mm for several years and above this mark for only 3 years. In the second half of the century, a wet period occurred resulting in consecutive years of high rainfall, alternating with years of drier than normal rainfall.

The correlation between SOI (1885-2011) and annual rainfall for the catchment (Table 1) was low (0.32). Annual correlation with the four selected stations was low: 0.27 (70057), 0.29 (68003), 0.30 (69010) and 0.30 (70012). During the negative phase of IPO, the catchment
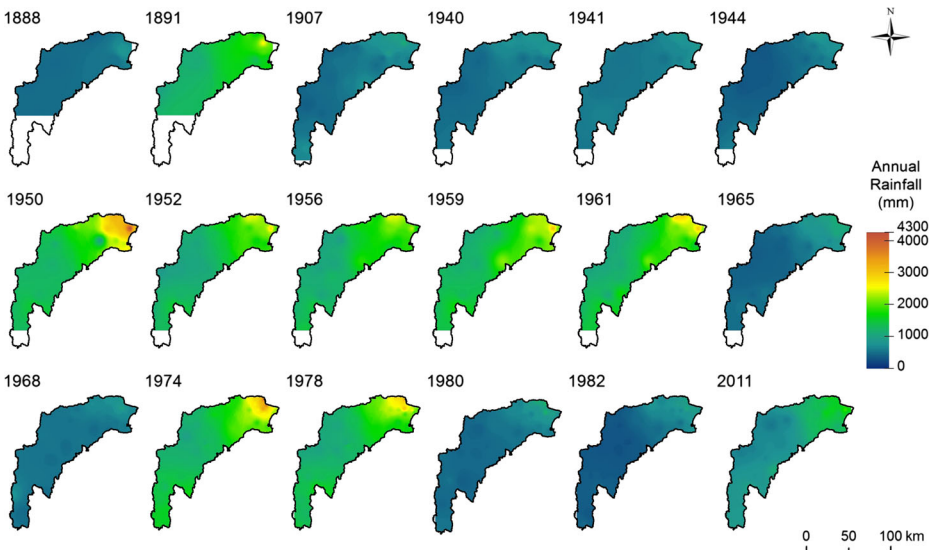
Fig. 4 Mean rainfall plots for selected years
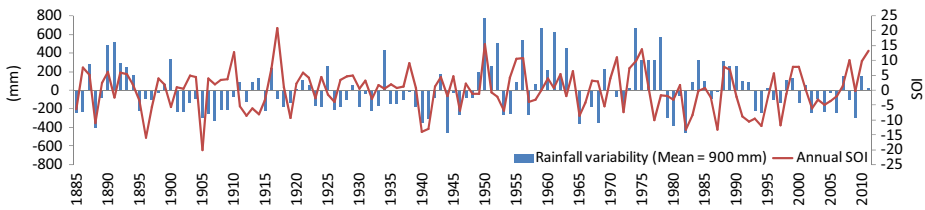
Fig. 5 Variation above/below mean annual rainfall for the Shoalhaven catchment (900 mm) from 1885 to 2011 and SOI.

correlation increased to moderate (0.51), while for selected stations it was 0.47 (70057), 0.48 (68003), 0.47 (69010) and 0.36 (70012).

3.2 Monthly Variability

Figure 6 depicts the spatial monthly distribution of rainfall in the Shoalhaven for the calendar year of 2011. March accounted for 14.5 % (133.3 mm) of the annual mean rainfall of 922 mm that occurred in the Shoalhaven catchment, but April, May and September accounted for less than 5 % each (Fig. 7). The rain gauge at 68197 in the coastal foothills recorded an annual total of 1910 mm of rainfall, while another 4 stations located in the lower end recorded above 1600 mm. These values were significantly different from stations located in the central and western parts of the catchment such as 68085 (604 mm), 70012 (560 mm), 70060 (617 mm) and 70342 (598 mm).

The monthly mean for the four rain gauges with long records are depicted in Fig. 8a. A marked increase in rainfall is observed at station 68003 when compared to the other three. Monthly mean is 118.4 mm at 68003, 65.6 mm at 70057, 59.9 mm at 69010 and 55.1 mm at 70012. The seasonal variability shows more distributed rainfall in the middle and upper stations than in the lower catchment (68003). A similar pattern with high rainfall in Jan-Mar and a marked peak in June is present.

Rain gauge 68003 had 50 months above 400 mm and was the only one to record monthly rainfall above 700 mm (Fig. 8b), with highest monthly records of 914.9 mm (Feb/1971), 812.5 mm (Nov/1961), 787.1 mm (May/1943) and 711.7 mm (Oct/1959). Station 70057 registered rainfall below 400 mm during all months except Oct/1959 (427.9 mm), Jun/1991 (449 mm), Aug/1974 (470 mm), Jul/1922 (482.8 mm) and May/1925 (685.8 mm). At station 69010 rainfall more than 400 mm occurred only twice, in Jun/1891 (517.1 mm) and May/1925 (663.9 mm), while at station 70012 this happened only once in Jun/1891 (405.5 mm).

Table 1 Correlation of annual rainfall with annual SOI and annual SOI during the negative phase of IPO

	SOI	SOI (Neg. IPO)
Shoalhaven catchment	0.32	0.51
68003	0.29	0.48
69010	0.30	0.47
70012	0.30	0.36
70057	0.27	0.47

The negative phase of IPO happened between 1946 and 1976, excluding 10 years from 1958 to 1967, when the absolute value of the IPO index was less than 0.5 (Power et al. 1999).
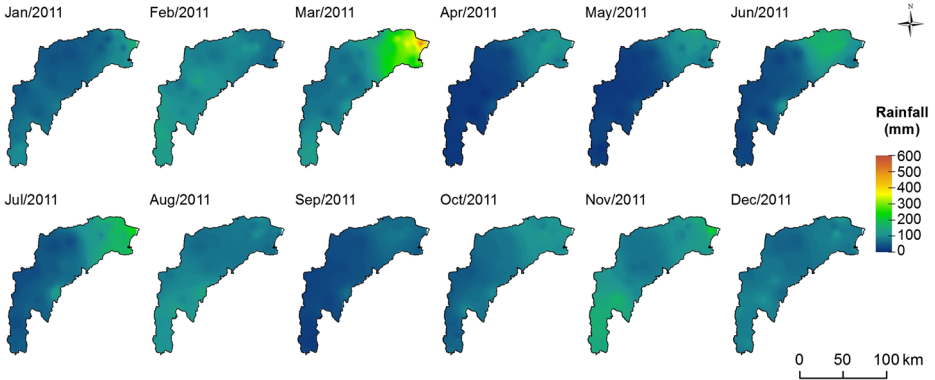
**Fig. 6** 2011 monthly rainfall variability in the catchment

The correlation between SOI (1885–2011) and monthly records (Table 2) was very low: 0.14 (70057), 0.13 (68003), 0.15 (69010) and 0.16 (70012). Lag correlations between SOI and rainfall in the following 12 months showed no improvement compared to the simultaneous ones. The best lagged relationships happened when rainfall lagged 2 months behind SOI, and for these correlations were: 0.1 (70057), 0.12 (68003), 0.09 (69010) and 0.11 (70012). During the negative phase of IPO, the monthly correlation increased slightly to 0.21 (70057), 0.19 (68003), 0.17 (70012), although at one site diminished to 0.07 (69010).

Using only spring months (Sep–Nov), the correlation between monthly rainfall and IPO remained weak for stations 69010, 70012 and 70057, and became very weak for 68003. Using the negative phase period of IPO, the spring correlation became very weak for station 69010 (0.14) and weak for the other 3 stations.

The correlation between the Atmospheric Blocking index (1950–2011) and monthly rainfall was very weak, however during the Apr–Oct period, was significant: 0.293 (68003), 0.378 (69010), 0.509 (70012) and 0.341 (70057).
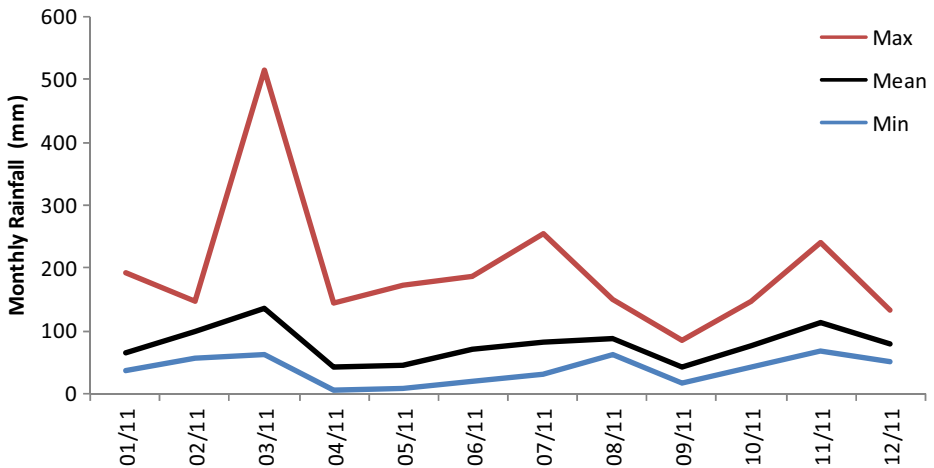
Fig. 7 Monthly mean of rainfall in the Shoalhaven catchment in 2011
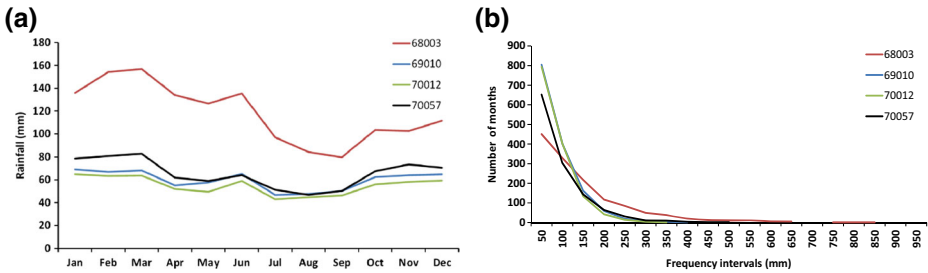
Fig. 8 Average monthly rainfall (**a**) and Frequency distribution of monthly rainfall (**b**) for long-record stations 68003 ($n=1483$), 69010 ($n=1487$), 70012 ($n=1420$) and 70057 ($n=1332$)

4 Discussion

Rainfall varied over the longer term in the Shoalhaven, with a clear increase in rainfall during the second half of the twentieth century relative to the first, especially between the 1950 and 1978, this general pattern is in accordance with the high/low rainfall period in southeast NSW identified by Kraus (1954), Pittock (1975), Cornish (1977), Srikanthan and Stewart (1991) and Warner (1995). Srikanthan and Stewart (1991) and Warner (1995) also observed high rainfall before 1900, which was also in accord with this study.

The increase in rainfall that started in 1950 may be primarily the result of an increase in summer (Dec–Feb) rainfall as illustrated by Nicholls and Lavery (1992). Before (after) 1950, average rainfall during summer were 196.4 (205.9) mm for station 69010, 383.8 (422.5) mm for 68003, 186.7 (188.8) mm for 70012, and 216.2 (242) mm for 70057.

The 2–3 fold disparity between the rainfall records in the coastal lower catchment when compared to the middle and upper catchment was observed in almost all years, especially during the wettest years. This does not mean that monthly rainfall was always higher in the lower catchment, as evidenced by the upper catchment rainfall in the months of Feb, Aug and Nov/2011, when more rain was recorded than anywhere else in the catchment, apart from a single station in the coastal foothills (68197) in Nov/2011. The greatest differences between records in the lower and middle/upper catchment happened in the months of Mar and Jul/2001.

The relationship between annual rainfall in the catchment and SOI revealed that there is a weak correlation between them that is improved to moderate during the negative phase of IPO as demonstrated in Table 1. This weak annual correlation is demonstrated not only by the

Table 2 Correlation of monthly rainfall with SOI, SOI during the negative phase of IPO, Spring SOI (Sep–Nov) and Spring SOI (Sep–Nov) during the negative phase of IPO[a], Atmospheric Blocking index and Atmospheric Blocking index during Apr–Oct.

Station	SOI	SOI (Neg. IPO)	Spring SOI	Spring SOI (Neg. IPO)	Atmospheric Blocking index	Atmospheric Blocking index (Apr–Oct)
68003	0.13	0.19	0.12	0.23	0.05	0.29
69010	0.15	0.07	0.27	0.14	0.13	0.38
70012	0.16	0.17	0.23	0.21	0.004	0.51
70057	0.14	0.21	0.21	0.2	0.08	0.34

[a] The negative phase of IPO happened between 1946 and 1976, excluding 10 years from 1958 to 1967, when the absolute value of the IPO index was less than 0.5 (Power et al. 1999).

average results for the catchment itself but also by the four long-record rain gauges. It is lower than results shown by Nicholls and Kariko (1993), who found moderate correlation (0.44) for a station located in Peak Hill (in the Central West of NSW) for the period between 1910 and 1988. This weak correlation found between annual ENSO and rainfall in the catchment and gauging stations is also in accordance with previous results that found that the influence of La Niña on rainfall tends to be greater in northern New South Wales and Queensland diminishing as one moves south into Victoria (Verdon et al. 2004).

During the strong events of La Niña in 1950 (SOI=15.4), 1956 (SOI=10.7) and 1974 (SOI=9.9), the catchment received substantially more rainfall than an average year, whereas the El Niño events in 1940 (SOI=−13.8), 1941 (SOI=−12.8) and 1982 (SOI=−13), resulted in less rainfall. Despite the good response in relation to these specific ENSO events, the general correlation with other strong events such as in 1917 (SOI=20.8), 1938 (SOI=9.1), 1971 (SOI=10.9), 1977 (SOI= –9.9), 1992 (SOI=−10.2) and 2008 (SOI =10.2) produced the opposite effect to that which was expected.

The improvements on the annual relationship during the negative phase of IPO are in accordance with findings concerning modulation of the magnitude of ENSO impacts, as pointed out by Power et al. (1999). The relationship between monthly rainfall and SOI was weaker than the annual correlation and no enhancement was achieved when compared to lagged months. In both, monthly and annual correlations, stations 69010 and 70012 were slightly more influenced by SOI than the other two. However, this pattern changed during the negative phase of IPO.

Verdon et al. (2004) found that every station they analysed in central, south NSW or Victoria increased its correlation with SOI during the IPO negative phase, however monthly results for station 69010 showed a twofold decrease. Apart from this station, the other 3 showed similar results to the findings of these researchers. Using only spring months (Sep– Nov), the correlation rose, as stated by McBride and Nicholls (1983), who showed that this season has the best relationship with SOI, despite the slight decrease noted in station 68003. Surprisingly, when the negative IPO was used with spring months, the correlation increased from 0.12 to 0.23 in 68003, decreased in 70012 and 70057, and became much weaker in station 69010.

The analysed rain gauges did not show influence of Atmospheric Blocking in all seasons, apart from a very weak relationship at 69010. However, between April and October, the correlation increased and reached a moderate relationship at station 70012, emphasising the importance of this climate driver during this period, as discussed by Risbey et al. (2009).

5 Concluding Remarks

This investigation has focused on climatic variability in the Shoalhaven catchment using 141 rain gauges to assess annual rainfall from 1885 to 2011. Average rainfall was ~900 mm for the catchment during this time-span, however much higher values happened between the decades of 1950 and 1970, while drier than normal years occurred in the beginning of 1940's, 1980's and the second half of 1960's. Maximum annual rainfall recorded by a gauge was 4300 mm at a station located in the coast foothills in 1950.

Monthly variability in the catchment was investigated through use of data from four long-record rain gauges and reconstruction of 2011 rainfall. The Shoalhaven catchment has a

spatially variable rainfall pattern with approximately twice the amount of rainfall in the lower catchment than further upstream. The months of Jan-Mar are responsible for~30 % of annual rainfall. Correlation between rainfall and the South Oscillation and the Atmospheric Blocking indices were not particularly strong. It appears that the rainfall in the catchment is weakly to moderately driven by SOI during the negative phase of IPO, despite the very low correlation of the analysed rain gauges, including during spring and lagged months. It can be positively related to the Atmosphere Blocking between April and October only.

These results imply that the widely held view that El Niño conditions, indicated by a highly negative SOI, are associated with drought years in southeastern Australia, is an oversimplification. Although this may have been the case in recent decades, as apparent from Fig. 5, the relationship is less clear over the longer term when modulated by IPO. At the catchment scale, it will remain a challenge to forecast rainfall, and it remains important to maintain rainfall records, and to further research the relationships between these and other climatic indices, and the source of precipitation. Water supply and floodplain management actions on the basis of these climatic indices should not be encouraged.

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