Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts

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[1] Three protracted droughts have occurred during the instrumental history of Southeast Australia (SEA) – the "Federation" (~1895–1902), "World War II" (~1937–1945) and the "Big Dry" (~1997–present). This paper compares the nature and causes of these droughts in order to better inform drought management strategies in SEA. It is shown that the three droughts differ in terms of severity, spatial footprint, seasonality and seasonal rainfall make-up. This diversity arises due to the fact that the droughts are driven by different climatic teleconnections with the Pacific, Indian and Southern Oceans. Importantly, this study highlights potential flaws with drought forecasting and management in SEA and emphasises the need for further research into understanding and representing hydroclimatic drivers of drought. **Citation:** Verdon-Kidd, D. C., and A. S. Kiem (2009), Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts, *Geophys. Res. Lett.*, *36*, L22707, doi:10.1029/2009GL041067.

1. Introduction

[2] A prolonged drought has affected Southeast Australia (SEA) since the mid-1990s. Known as the "Big Dry", this drought has had serious impacts on agricultural production (due to decreased irrigation allocations), biodiversity (due to prolonged changes in habitats), bushfire regimes and water availability for industrial and consumptive use. Not surprisingly, the Big Dry has attracted a great deal of media attention, along with labels such as "worst drought on record". However Australia, with its highly variable climate, is no stranger to such drought conditions. For example, the "Federation drought" (~1895–1902) was associated with drought conditions covering the majority of the eastern two thirds of Australia. From 1937—1945 SEA was subjected to yet another multi-year drought, known as the "World War II (WWII) drought". In addition to the three multi-year droughts mentioned, a number of shorter, equally intense droughts have also occurred during Australia's instrumental history (e.g., 1914–1915, 1965–1968 and 1982–1983).

[3] Despite the regular occurrence of prolonged droughts in SEA, a comparative study has not been carried out to determine how the Big Dry compares, in terms of nature and causal processes, to other multi-year droughts. Furthermore, research to date has focused on identifying a single climate phenomena/process to explain the Big Dry [e.g., *Ummenhofer et al.*, 2009; *Larsen and Nicholls*, 2009; *Taschetto and England*, 2009]. This has lead to conflicting opinion as to the cause of the Big Dry with candidates currently including the Indian Ocean Dipole (IOD), Subtropical Ridge (STR), El Niño/Southern Oscillation (ENSO), ENSO Modoki and various anthropogenic influences.

[4] *Risbey et al.* [2009] showed that individual drivers, when treated as a single process, account for less than 20% of monthly rainfall variability for most Australian regions. Therefore it is unlikely that a single climate phenomenon was responsible for all drought events in SEA, rather, different dry epochs are likely to be driven by different and/or multiple climate processes [e.g., *Nicholls*, 2009; *Kiem and Verdon-Kidd*, 2009]. Therefore, this paper aims to provide a comparative analysis of the nature (in terms of rainfall deficiencies) and causes (in terms of remote climate drivers) of the three major protracted droughts that have occurred during the instrumental record in SEA - the Federation drought, WWII drought and the Big Dry.

2. Data

[5] This analysis is focused on rainfall rather than streamflow, or any other drought related variable. This is because streamflow is impacted by additional mechanisms (e.g., soil moisture, seasonality and intensity of rainfall, land cover change, extractions, loss to groundwater etc.) which are unlikely to be constant during the three periods of interest (i.e., 1895–2002, 1937–1945, 1997–present). The Australian Monthly Gridded Rainfall Dataset from the Australian Bureau of Meteorology (BoM) is used to assess the spatial extent of the three droughts. The gridded data spans the period 1900–2008, providing limited information on the Federation drought. To overcome this, along with gridded data issues relating to interpolation and smoothing of extreme events, additional point source data from 12 stations located in SEA is used to characterise the droughts. The stations chosen for analysis (Figure 1a) have sufficiently long records (i.e., spanning all three droughts) and minimal missing data (i.e., at least 99% complete).

3. Results

3.1. Comparison of Annual Rainfall

[6] The average annual rainfall deficiency across SEA during the three major multi-year droughts compared to the long term mean (based on the period 1900–2008) is shown in Figure 1, while Table 1 displays the results for the 12 individual rainfall stations. Note that in this study the Big Dry is defined as the period 1997–2008, however there is some evidence the drought may have initiated as early as 1994 [*Kiem and Verdon-Kidd*, 2009].

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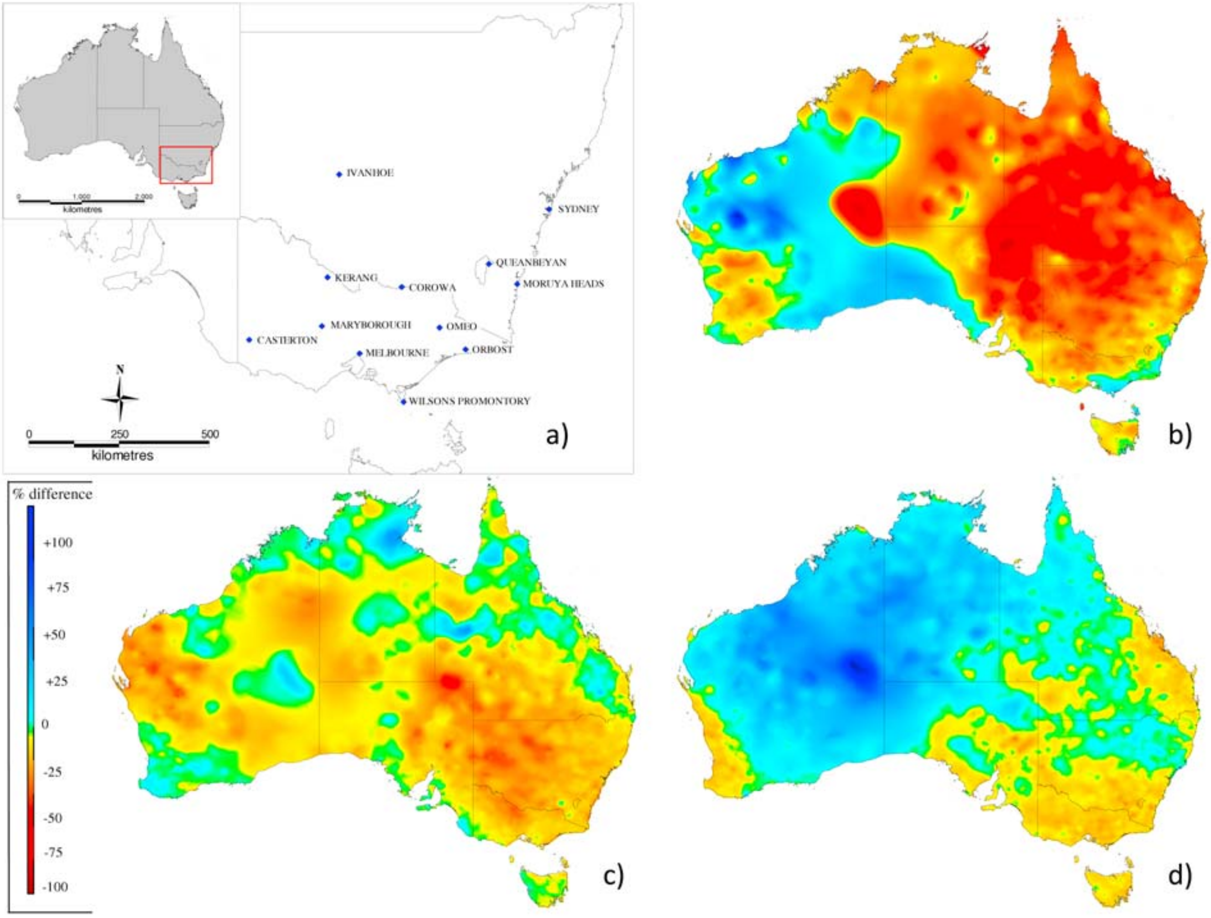

Figure 1. (a) Location of 12 rainfall stations in SEA, annual average rainfall deficiencies during (b) Federation, (c) WWII, and (d) Big Dry droughts. Note that a decrease of 50% indicates that the rainfall received during the drought was only half the long term average.

[7] It is clear from Figure 1 and Table 1 that the three droughts have a very different spatial signature and magnitude of impact. The Federation drought was concentrated in northern and eastern Australia (and parts of SW Western Australia) and is the most severe of the three droughts for much of New South Wales (NSW) and Queensland (QLD), however the SE coastal regions appear to have escaped severe drought. The WWII drought extended across much of the country and is the only drought of the three studied to have affected NW and SE Australia simultaneously. Figure 1c shows that the Big Dry is confined to SEA, SE QLD and SW Western Australia, with above average rainfall observed elsewhere, particularly NW Western Australia.

3.2. Comparison of Seasonal Rainfall

[8] Numerous studies have demonstrated that, rather than a decline in rainfall across all seasons, the main reason for extremely low runoff in SEA during the Big Dry is the disproportionately large decline in autumn/early-winter rainfall [e.g., *Murphy and Timbal*, 2008; *Pook et al.*, 2008; *Kiem and Verdon-Kidd*, 2009]. This raises the question – did the Federation and WWII droughts also exhibit seasonality in the rainfall decline? This is investigated in Figure 2, where seasonal rainfall reduction compared to the long term mean is shown for each station.

[9] In Figure 2 the dominant autumn rainfall decline during the Big Dry is evident for most stations (particularly those located in the north of the study region), consistent with previous findings. Generally, the Federation and WWII droughts do not follow the same seasonal trend as the Big Dry. For example, Figure 2 shows that the Federation drought was predominantly due to rainfall reductions in spring/summer. During the WWII drought, rainfall was

Table 1. Annual Average Rainfall Deficiency Compared With Long Term (1900–2008) Mean During the Federation, WWII, and the Big Dry Droughts for Selected High Quality Stations

Station Location	Federation Drought (1895–1902)	WWII Drought (1937–1945)	Big Dry (1997–Present)
Ivanhoe	−18%	−41%	−12%
Sydney	−6%	−14%	−7%
Queanbeyan	−17%	1%	−5%
Kerang	−29%	−35%	−3%
Moruya	−2%	−4%	−12%
Corowa	−19%	−18%	−14%
Maryborough	−16%	−29%	−19%
Omeo	−7%	−9%	−11%
Casterton	−11%	−9%	−12%
Orbost	−8%	−10%	−9%
Melbourne	1%	−16%	−23%
Wilsons Prom	2%	0%	−16%

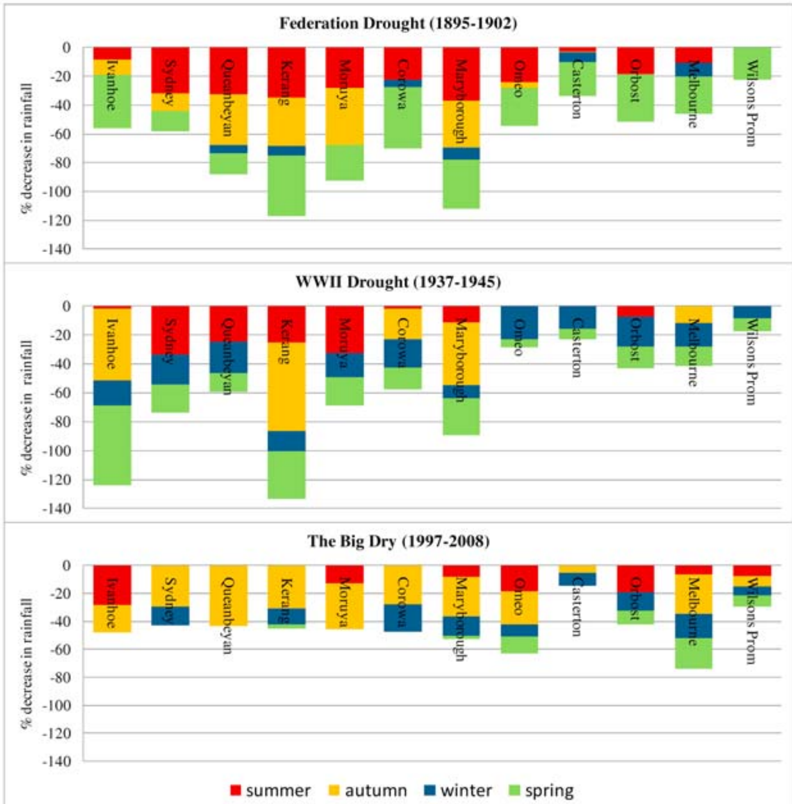

Figure 2. Seasonal average rainfall deficiencies during the Federation, WWII, and Big Dry droughts.

reduced across all seasons, however there does appear to be some spatial variability – with stations located in the NW of the study region displaying a larger autumn rainfall decline, stations located along the coastal fringe of NSW exhibit a summer decline, while the SE displays marked winter/spring rainfall deficiencies.

3.3. Comparison of Daily Rainfall

[10] Changes in daily rainfall statistics (i.e., changes to the frequency, intensity, duration and/or sequencing of rainfall events) have important hydrological implications, as this will influence soil moisture and runoff generated [e.g., *Kiem and Verdon-Kidd*, 2009]. The average number of wet days per year (defined as any day with rainfall greater than 1 mm) and the average daily rainfall intensity during the three droughts is shown in Table 2. The results are presented as a percent difference compared to long term average.

[11] Table 2 shows the Federation drought was primarily caused by a decrease in the number of rain days rather than a change in the rainfall intensity. During spring this decrease is striking (~25% on average). The opposite is true for the Big Dry, where a decrease in the rainfall intensity, rather than number of rain days, appears to be the primary driver – particularly during autumn (~25% decrease in intensity on average). This result is consistent with recent work by *Pook et al.* [2008] and *Verdon-Kidd and Kiem* [2009] who showed that the frequency of synoptic patterns associated with intense rainfall across SEA has reduced markedly during autumn since 1994. Both the average daily intensity and number of rain days was reduced during the WWII drought and again there appears to be strong spatial variability in the impacts.

3.4. Causal Mechanisms

[12] Numerous studies have demonstrated that the four most influential climate modes on SEA's climate are:

[13] 1. El Niño/Southern Oscillation (ENSO) – coupled ocean-atmosphere variability that manifests as abnormal warming (El Niño) and cooling (La Niña) of the tropical Pacific Ocean. El Niño tends to result in warm dry conditions in SEA, while the reverse is true for La Niña [e.g., *Chiew et al.*, 1998; *Kiem and Franks*, 2001; *Verdon et al.*, 2004].

[14] 2. Inter-decadal Pacific Oscillation (IPO) – a low frequency (15–35 years) pattern of variability of the tropical and extra-tropical Pacific ocean (refer to the work of *Power et al.* [1999] for details). The IPO appears to modulate the strength and frequency of ENSO events, whereby the positive (negative) phase is associated with a higher frequency of El Niño (La Niña) events and suppressed (enhanced) impacts of La Niña [*Power et al.*, 1999; *Kiem et al.*, 2003; *Verdon et al.*, 2004]. Also see *Power and Colman* [2006] regarding the origins of the IPO and issues with reliability pre-1950.

[15] 3. Indian Ocean Dipole (IOD) – a coupled ocean-atmosphere climate mode that occurs inter-annually in the tropical parts of the Indian Ocean. During a positive IOD event, the sea-surface temperature (SST) drops in the northeast Indian Ocean (near the NW coast of Australia)

Table 2. Comparison of the Number of Wet Days Per Year and Average Daily Rainfall Intensity for Each of the Three Droughts[a]

Station	Federation				WWII				Big Dry			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
% Difference in Number of Wet Days Per Year												
Ivanhoe	**−14**	**−26**	**3**	**−30**	−38	**−36**	**−22**	**−40**	4	**−13**	6	0
Sydney	−10	**−13**	25	**−11**	−27	−2	6	0	−4	−7	−3	−1
Queanbeyan	**−35**	**−30**	**−22**	**−19**	−20	−8	**−12**	**−7**	28	**−23**	29	2
Kerang	**−34**	**−32**	**−17**	**−43**	−17	**−33**	**−20**	**−27**	16	**−16**	−8	−4
Moruya	**−16**	**−15**	24	**−19**	−5	0	3	−1	−1	**−14**	−2	−8
Corowa	**−31**	**−17**	**−16**	**−38**	−26	**−16**	**−16**	**−16**	−4	**−20**	**−13**	−8
Maryborough	47	58	−8	**−29**	−13	−6	**−14**	**−17**	−4	**−21**	**−15**	−4
Omeo	**−16**	8	5	**−22**	−5	5	**−11**	**−7**	−2	**−15**	−5	−3
Casterton	−9	10	**−11**	**−12**	21	−4	−3	**−11**	−6	−8	−5	3
Orbost	**−24**	**−13**	24	**−32**	0	12	−4	**−5**	11	−1	−5	5
Melbourne	0	2	−4	**−21**	−4	0	−1	**−11**	−12	**−20**	**−21**	**−17**
Wilsons Promontory	−10	−6	−6	**−14**	12	8	6	3	−5	**−13**	**−11**	**−5**
% Difference in Average Daily Rainfall Intensity												
Ivanhoe	**−19**	**−14**	**−5**	**−22**	−4	4	**−11**	**−8**	−34	**−41**	**−18**	**−12**
Sydney	**−26**	**−18**	5	−7	**−21**	**−3**	**−21**	**−14**	−3	1	15	−1
Queanbeyan	11	12	38	13	**−15**	**−20**	**−30**	**−19**	−13	**−29**	−5	**−15**
Kerang	24	37	41	20	**−21**	**−27**	−7	**−10**	−22	**−34**	**−21**	**−9**
Moruya	9	−3	41	**−19**	0	32	**−18**	5	**−13**	**−30**	18	−6
Corowa	18	19	23	−1	−9	15	−3	**−11**	−5	**−15**	**−11**	−10
Maryborough	−2	−5	17	0	**−19**	**−22**	−4	**−13**	−12	**−36**	**−29**	**−18**
Omeo	8	5	4	**−7**	7	13	3	12	**−23**	**−36**	**−18**	**−17**
Casterton	11	−5	14	**−14**	12	−8	−7	−10	−8	**−16**	**−16**	1
Orbost	55	50	58	51	**−17**	5	**−24**	2	**−29**	**−31**	**−15**	**−26**
Melbourne	2	21	0	**−18**	−4	**−11**	−9	−5	−9	**−10**	−2	**−10**
Wilsons Promontory	24	19	4	**−12**	−7	3	−8	−10	**−19**	**−16**	−5	**−13**

[a]Percentage difference is in reference to the long term mean and decreases of more than 10% are in bold.

while the SST rises in the western equatorial Indian Ocean. Inverse conditions exist during a negative IOD event. Positive (negative) IOD events tend to result in reduced (enhanced) winter and spring rainfall in SEA [e.g., *Verdon and Franks*, 2005].

[16] 4. Southern Annular Mode (SAM) – the leading mode of atmospheric variability over the southern extratropics. The SAM represents an exchange of mass between the mid latitudes and the polar region [*Thompson and Wallace*, 2000] which modulates westerly winds over the southern extratropics and embedded frontal weather systems. The positive phase of SAM has been associated with reduced autumn rainfall in SEA via a reduction in frontal systems [e.g., *Verdon-Kidd and Kiem*, 2009; *Nicholls*, 2009].

[17] Figure 3 shows the timeseries of ENSO (represented by the Niño3.4), IPO, NW of Australia SSTs (eastern pole of the IOD) and SAM, along with the three protracted drought epochs. See *Verdon-Kidd and Kiem* [2009] for a description of these indices. NW of Australia SSTs are used here rather than the IOD as previous studies have shown that warming to the NW of Australia (i.e. the eastern pole of the IOD) is most important for cloud band development and strongly related to above average rainfall in SEA [e.g., *Verdon and Franks*, 2005], while the need for an anomaly further west has not been demonstrated. In fact the poles of the IOD are not negatively correlated as one would expect [*Dommenget and Latif*, 2002] and intermittent decoupling of the east and west pole of the IOD can lead to false classification of events. It should also be noted that the STR is suggested to have played a significant role in the recent drought [e.g., *Larsen and Nicholls*, 2009], however data is not available for the STR prior to 1950 and therefore STR was not included in this analysis. The instrumental record of the SAM (available from 1957 to present [*Marshall*, 2003]) has been extended using *Jones et al.*'s [2009] reconstruction.

[18] It is evident that the Federation drought occurred during a period of sustained El Niño activity (as indicated in Figure 3 by the warm SSTs in the Niño3.4 region), with only 1898 reaching the La Niña threshold. Furthermore, the impacts of this lone La Niña might have been suppressed since it occurred during an IPO positive epoch [e.g., *Verdon et al.*, 2004]. SSTs off the NW of Australia (eastern pole of IOD) were warm during the Federation drought suggesting that the Indian Ocean variability was not a major contributor to this drought. Likewise the SAM index was predominantly negative and, taking this result at face value (ignoring concerns over its reliability prior to the 1950s), suggests that SAM was unlikely to have contributed to the rainfall decline. These results (i.e., ENSO and IPO being primary drivers of Federation drought) are consistent with the observed spatial footprint and seasonality of the Federation drought (Section 3) given the greatest impact of El Niño on rainfall in SEA is during the spring/summer months and the magnitude of impact is greater in NE Australia than SE. Further, *Verdon-Kidd and Kiem* [2009] found that El Niño events were associated with a weakening and northward retraction of the easterly trough, also consistent with the observed reduction in the number of rain days.

[19] Figure 3 demonstrates that ENSO switched between El Niño and La Niña conditions during the WWII drought (with slightly more El Niño years) and the SAM alternated between its positive and negative phase, indicating that neither persistent El Niño conditions nor positive SAM caused the WWII drought. However, SSTs off the NW coast of Australia (the eastern pole of the IOD) were cooler than average for six out of the nine years during the WWII drought, suggesting that the Indian Ocean is a likely contributor to this drought. This finding is consistent with

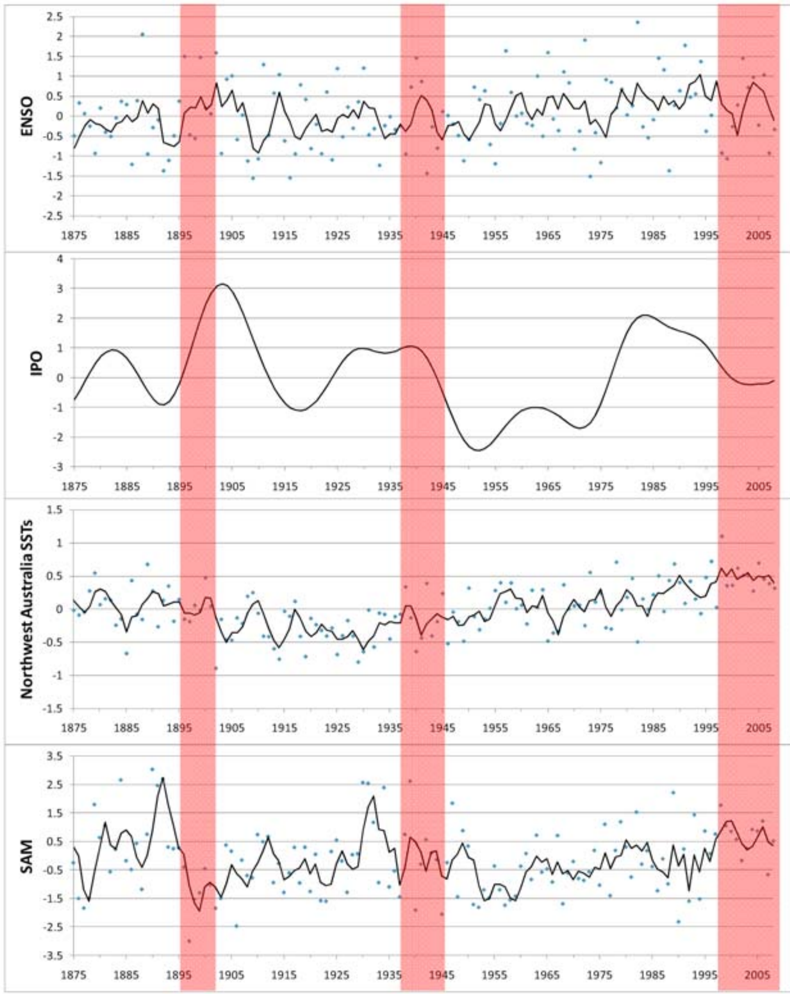

Figure 3. Historical timeseries of ENSO, IPO, NW of Australia SSTs and SAM. Dots represent the mean 'annual' value for each index, solid line is the 3 yr moving average, red shaded regions indicate the three major droughts.

observed reductions in winter/spring rainfall (which is when the IOD is dominant) and the clear NW-SE signature of the drought across the country (Figure 1c). However, Figure 3 also exhibits other periods of persistently negative SSTs off NW Australia in the last 100 years – in fact the whole period from 1910–1945 was predominately below average. So why wasn't this entire period dry? The key is the sequencing of the years during the drought. Of the three La Niña events that occurred during the WWII drought, two occurred in combination with a positive SAM. *Kiem and Verdon-Kidd* [2009] have shown that SAM acts to block the propagation of La Niña rainfall into SEA (indeed La Niña can be as dry as El Niño in SEA when the SAM is positive). In addition, the IPO was positive during this period which might have also acted to suppress the impact of La Niña.

[20] Figure 3 suggests that SAM is a major causal factor of the Big Dry, with a sustained positive epoch occurring from 1997–present. In addition, there were three consecutive El Niño events (2002–2004) during the peak of the drought and a complete lack of La Niña from 2000–2006. The La Niña events of 2007/2008 did not result in drought breaking rain for SEA because the SAM was strongly positive during this time. Although, in areas to the north of SAM's reach (i.e., QLD and northern NSW) the 2007/2008 La Niña did in fact break the drought. NW Australian SSTs have been warmer than usual since 1985, suggesting that Indian Ocean variability is unlikely to have been a major driver of the Big Dry (contrary to the findings of *Ummenhofer et al.* [2009]). The dominance of the SAM in the current drought is consistent with autumn rainfall decline observed during the Big Dry, since this is the season where SAM has been most consistently positive since the mid-1990s [*Kiem and Verdon-Kidd*, 2009]. Further, the fact that the spatial signature of the Big Dry (Figure 1d) shows drought being focused on SEA and southwest WA is consistent with a reduction in pre-frontal systems, which in turn is symptomatic of a positive SAM phase [e.g., *Verdon-Kidd and Kiem*, 2009].

[21] It is also worth noting from Figure 3 that the short but intense 1982–1983 drought (worst on record in terms of short-term rainfall deficiencies) occurred when the Pacific was in an El Niño IPO positive state, the waters off NW Australia were cool and the SAM was positive (i.e., all four modes locked into their dry phase).

4. Discussion

[22] The Federation, WWII and Big Dry droughts are the three longest droughts on instrumental record in

SEA – though similarities between them end there. Each drought is quite dissimilar in terms of severity, spatial signature, seasonality and seasonal rainfall make-up. Results presented here suggest this is because each drought was driven by a different climate process (or combination of processes). Importantly, these results highlight some major issues with drought management and forecasting in SEA, in particular:

[23] 1. It is now understood that droughts in SEA are associated with at least four major climate phenomena (ENSO, IPO, IOD and SAM). This raises the questions – have we experienced the worst drought possible in SEA? What if we were to experience a situation identical to the 1982/1983 event (when all four modes were locked into their dry phase) sustained over a longer period of time? How likely is this situation to occur? Answers to these questions require study of the pre-instrumental history combined with utilisation of stochastic frameworks to more robustly quantify the risk of drought. Climate model projections should also satisfactorily account for the natural variability mentioned above and then be interrogated to provide insight into the degree to which anthropogenic climate change contributes to the current drought (the Big Dry) and if/how the risk of drought may change in the future.

[24] 2. To date forecasting schemes have focussed on predicting ENSO (with some effort now being directed towards forecasting IOD). However, even a perfect ENSO forecast will not suffice in predicting protracted droughts in SEA. Indeed, climate forecasting systems will need to account for all climate modes, and their interactions, in order to be successful.

[25] Further understanding into how multiple physical mechanisms, including anthropogenic climate change, interact to drive SEA climate, and improved conceptualisation and representation of these interactions in dynamical climate models (both regional and global models), is required if we are to satisfactorily predict onset and conclusion of drought. Failure to address these issues will result in drought management strategies continuing to be largely ineffective in reducing Australia's vulnerability to drought.

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