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Reply on RC2

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Interactive comment on "Regime transitions of Australian climate and climate extremes" *by* Jorgen S. Frederiksen and Stacey L. Osbrough

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We are pleased to learn that the Referee thinks that the main idea in the paper is interesting and deserves to be published. Here we present a summary of how we have addressed the Reviewer's comments with more details in Response to RC2 (Part 2) accompanying the revised paper.

1 Motivation and summary of findings for major sections

We have added questions to be answered at the start of the major sections and a summary of findings at the end. The conclusions provide further summaries of our findings. We are interested in both the timings of the transition periods and how this varies regionally or not. Much of the discussion on anthropogenic climate change tipping points has focussed on major tipping points of global extent that may be exceeded in the future. For example, Lenton et al. (2019) discuss tipping points such as the possible acceleration of the melting of the Greenland ice sheet that could occur with a 1.5^{o} C warming. As noted, our particular interest in this article is whether the changes that have already occurred in Australian climate and climate extremes over the last seventy years are indicative of regime transitions in a noisy environment. Further discussion on the aims and purpose, and main findings, is given in the main sections of the paper that have been updated. We also discuss the relationship between these changes and the large-scale circulation and in the revision further expand on additional implications and connections.

2 Data and Methods 2.1 Rainfall, temperature and streamflow data sets

The average and extreme – decile 10 – rainfall and temperature data used in this paper have been obtained from the Bureau of Meteorology (2022a) website. In this study we focus on various regions such as SWWA, SEA, Northern Australia, and Australian states, shown in Fig. 1. These Bureau of Meteorology (BoM) data sets are based on averages of station data and are of higher quality than earlier BoM data sets (Jones et al., 2009; Trewin 2013). Gridded data sets based on observed station data are also generally more consistent than reanalysis data sets particularly in the pre-satellite era (e.g., Donat et al., 2014). The data for streamflow into Perth dams has been obtained from the Water Corporation (2020) of Western Australia.

2.2 Reanalysis data sets

The investigation of the changes in atmospheric circulation in our study uses the reanalysis data set of the National Centers for Environmental Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR), (Kalnay et al., 1996). It will be referred to as the NNR data set. The NNR data set is available for the whole period from 1948 to the present and has been one of the most studied reanalysis data set incorporating the pre-satellite period. We focus here on changes in the Southern Hemisphere zonal jet in the Australian region and their strong relationships to rainfall changes in Southern Australia. In Supplement S1, we summarize the results of studies of the comparison of the NNR data set in the Australian region with other reanalysis data sets and with observations.

2.3 Methods

Next, we summarize the method of determining decile data from the BoM station data and our method for establishing the changing trends and critical points in data sets.

2.3.1 Determination of decile data

Gibbs and Maher (1967) developed a decile-based methodology for characterizing meteorological drought and presented Australian maps of the distribution of decile ranges of annual rainfall for the years 1885 to 1965. This method of determining decile data from station rainfall data (Jones et al., 2009) and temperature data (Trewin 2013) is detailed on the websites of the Bureau of Meteorology (2022b, 2022c). Briefly, deciles are a convenient way of coarse-graining the frequency distribution of a variable into ten bands each with 10% of the values. Decile 1 corresponds to the lowest 10%, decile 5 gives the median and decile 10 the highest 10% of the data which is generally monthly, seasonal, multi-month or annual data. The method makes no assumption about the distribution – it is nonparametric – and is based on all the data for a given time span. In practice, for a given time span, gridded data in each grid box, are sorted from lowest value to highest value and placed into ten equal bands, labelled decile 1 to 10, so that any value in a lower decile is smaller than those in the next decile. The percentage of grid boxes (percentage area) with values in a given decile and year and in a particular geographical region are then calculated based on all the grid boxes, which may be as small as circa 5 km by 5 km (0.05 degrees by 0.05 degrees) for regional rainfall.

The utility and applications of decile data is further described in Supplement S2.

2.3.2 Determination of changes in trends and critical points

The critical times of large and sustained changes in the trends of the rainfall, streamflow and temperature data considered in this study have been determined as follows. The data have been low-pass filtered by applying a 10 year running mean to reduce noise due to the interannual variability. Graphs of the filtered data indicate time periods when these trends change significantly. Regression of the filtered data against time over each time periods incorporating these trend changes are then used to focus in on the critical times. Firstly, regression is applied against a quadratic function of time which highlights the critical time of gradient change. Then regressions against linear functions of time are performed between the beginning and first critical time, between the last critical time and the end of the timeseries and between any two adjacent intermediary critical points. This then determines the large changes in linear trends we find that are sustained for 15 to 20 years or longer. Averages of the unfiltered data are calculated for the associated time periods.

S1 Reanalysis data sets and observations

We have noted the consistency between aspects of the large-scale circulation in the Australian region as characterized by the NCEP-NCAR reanalysis data set (Kalnay et al., 1996) (hereafter NNR) and Southern Australian rainfall in this study and in our earlier works discussed in the Introduction. In our earlier works (e.g., Frederiksen et al., 2017) we also compared results based on NNR reanalyses with those for European Centre for Medium Range Weather Forecasting (ECMWF) Reanalysis (ERA-40) project (Kållberg et al., 2007) and Twentieth Century Reanalysis (20CR v2) project (Compo et al., 2011) that include the pre-satellite era. Here we consider the relationships between NNR reanalyses and other reanalyses and observations in the Australian region including during the pre-satellite era.

Hertzog et al. (2006) compared the results of the August 1971 to December 1972 EOLE (from the Greek God of the Winds) experiment, involving flights of super-pressure balloons in the Southern Hemisphere upper troposphere, largely between 230 hPa and 190 hPa and 20S-70S, with NNR and ERA-40 data. They argued that their findings are representative of reanalysis accuracy for the pre-satellite era between 1957 and 1979. They noted that their analysis of the zonal wind structure in their Fig. 6 shows that both NNR and ERA-40 largely capture the meridional structure of the mean upper tropospheric jet although ERA-40 has a spurious double-jet peak structure. As well, ERA-40 has much larger errors in capturing upper tropospheric synoptic-scale variability. ERA-40 also has larger errors than NNR in representing mean sea level pressure and 500 hPa geopotential heights in the mid to high latitudes of the Southern Hemisphere in the pre-satellite era as shown in Figs. 3 and 6 of Bromwich and Foght (2004).

Frederiksen and Frederiksen (2005, 2007; hereafter FF05, FF07) found broad consistency between changes in the Southern Hemisphere July large-scale circulation determined by NNR data, and the results of instability calculations of synoptic disturbances based on this data, and changes in rainfall over south-west Western Australia before and after the mid-1970s. FF07 (Table 7) also compared results for ERA-40 data with those for NNR and found very close agreement for leading synoptic scale modes with growth rates differing by less than 4% and pattern correlations between 0.94 and 0.99. The similar weakening of the mid-winter Southern Hemisphere subtropical jet at 200 hPa around the Australian region, in both NNR and ERA-40 data, in the 1990s compared with the 1950s and 1960s, was also noted by Joseph and Sabin (2008; Fig. 4).

Frederiksen et al. (2017; Figs. 1 and 2) compared the Southern Hemisphere linear trend in Phillips (1954) criterion (discussed in our Section 3.2), in each of the four seasons, for NNR and 20CR v2 over the period 1950-1999 and for ERA-40 over 1958-1999. Of particular interest here are the consistent negative trends in the criterion upstream of Australia in NNR and ERA-40 with generally poorer agreement with 20CR. Rikus (2018), in a study of mid-latitude jetstreams in 9 reanalyses, including NNR, ERA-40 and 20CR, over the period 1979-2009, noted that 20CR had some systematic biases in upper-level winds compared with the the other reanalyses. Nevertheless, as shown in Fig. 1 of Freitas et al. (2015), the mid-winter reduction in the Southern Hemisphere subtropical jet that occurred in NNR data between the periods (1949-1968) and (1975-1994), and the increase further south, is evident in 20CR v2 data but with peak values at slightly lower levels, consistent with the findings of Rikus (2018).

The study of Osbrough and Frederiksen (2021), based on six hourly NNR 850 hPa data, found there was good correspondence between the reduction in fast growing storms in the Australian region since the late 1960s and the reduction in Southern Australian rainfall providing further evidence of the general consistency of NNR data with rainfall variability.

S2 Utility and applications of decile data

Since the first introduction by Gibbs and Maher (1967), the decile representation of meteorological data has been widely used in the study of droughts and rainfall and temperature variability. As noted in Section 2, the decile data is available from the website of Bureau of Meteorology (2022a) and the decile method is described on the websites of Bureau of Meteorology (2022b, 2022c). Decile data for seasons, extended seasons and years have been presented in many reports (e.g., Bureau of Meteorology and CSIRO 2020) and BoM publishes Australian maps of annual rainfall deciles from 1900 to the present (Bureau of Meteorology 2022d). Deciles of rainfall and temperatures have also been used in the horticultural and agricultural industries. For example, cool season – April to October – rainfall deciles were used in the South Australian Government study of climate change, wheat production and erosion risk by Sweeney and Liddicoat (2012). In a study of "The Riverland Climate for Almond Production" Thomas and Hayman (2019) examined September – April deciles of temperature. Hayman and Hudson (2021) explored the value of recent new BoM forecast products of weekly, monthly, and seasonal rainfall and temperature deciles for grain production.

Keyantash (2021) reviewed indices of meteorological and hydrological drought and compared the established quantile methodology of deciles with other approaches. He noted the simplicity and nonparametric nature of deciles that make no assumption about the distribution function but determines a coarse-grained version directly from the total available data. Keyantash and Dracup (2002) noted that, in the USA context, for Meteorological Drought the rainfall decile index as used at BoM is the superior index overall and particularly in terms of robustness, transparency and extendability (their Table 3). In the Handbook of Drought Indicators and Indices by the World Meteorological Organization and Global Water Partnership (2016) some of the properties of deciles are noted. In particular: deciles are "easy to calculate" and "examples from Australia are useful". "Daily, weekly, monthly, seasonal and annual values can all be considered in the methodology, as it is flexible when current data are compared to the historical record for any given period.". "Applications: With the ability to look at different timescales and time steps, deciles can be used in meteorological, agricultural and hydrological drought situations." Table 2 of the Handbook also lists some of the Meteorological Institutions, in addition to those in Australia and USA, that use deciles.

3 Presentational and minor comments

The Referee's presentational and minor comments will also be answered in Response to RC2 (Part 2) accompanying the revised paper.

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