Evidence of Climate Change in South-East Australian Water Data

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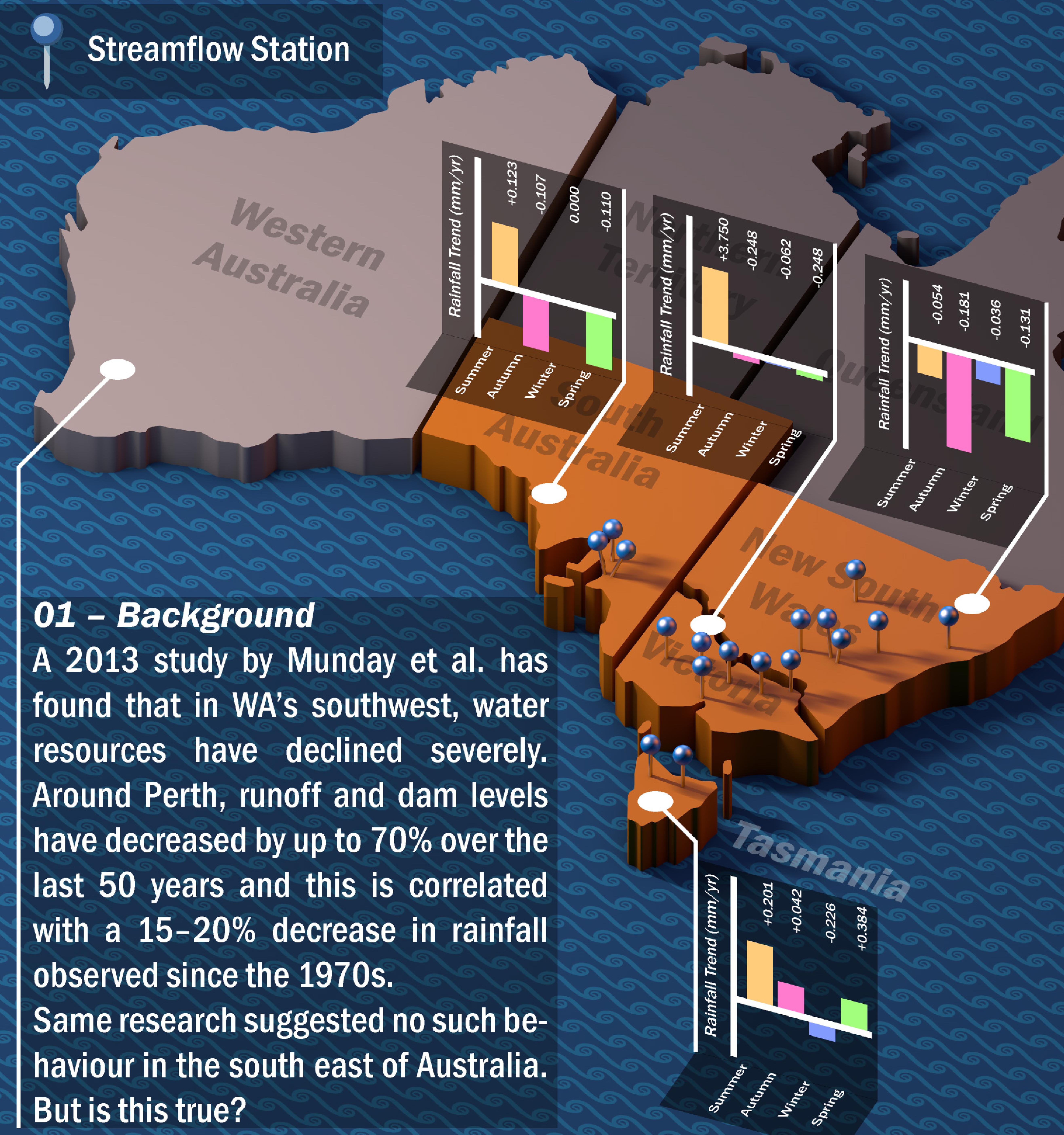
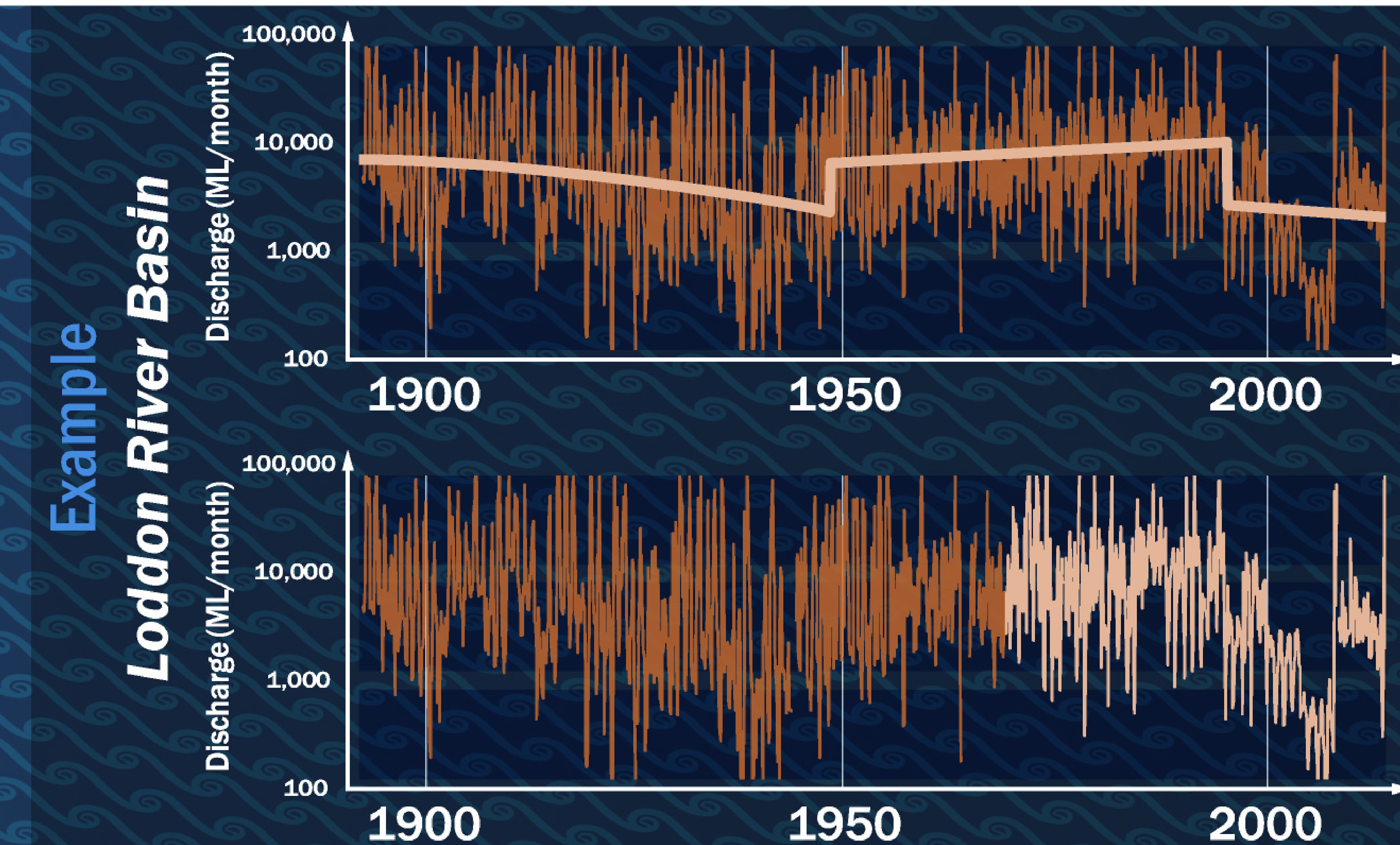


01 – Background

A 2013 study by Munday et al. has found that in WA's southwest, water resources have declined severely. Around Perth, runoff and dam levels have decreased by up to 70% over the last 50 years and this is correlated with a 15–20% decrease in rainfall observed since the 1970s.
Same research suggested no such behaviour in the south east of Australia. But is this true?

02 – Methodology

Non-Parametric tests to extract linear trends, break points, and their statistical significance.
Parametric tests to analyse magnitudes. Samples were chosen in 5 year increments from 1970 to 1995 (e.g. 1880-1969 vs 1970-2016, then 1880-1974 vs 1975-2016, etc.)

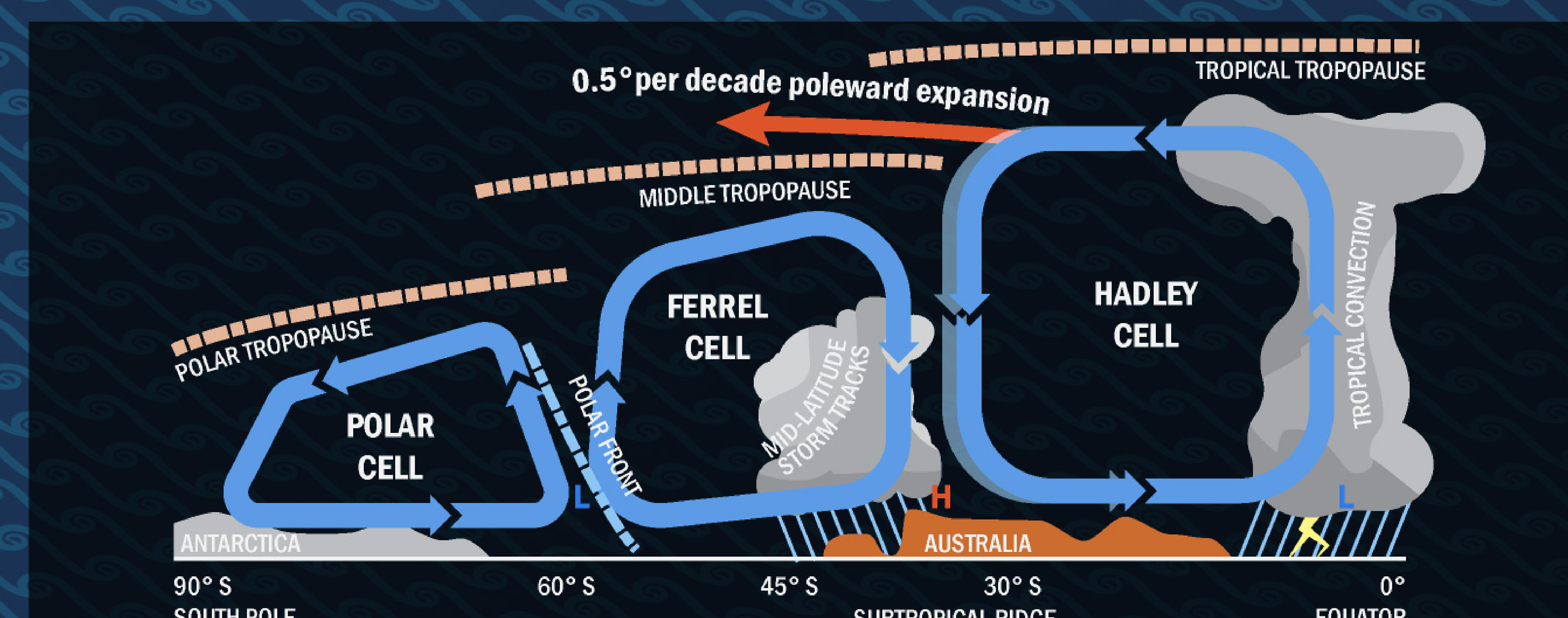


03 – Results

Over the 17 stations studied, greater changes are detected in streamflow than in rainfall. This is expected as elasticity between the two is 2.0–3.0 over the region. Annual results suggest reductions in peak flows, particularly from 1950 onwards but trends in rainfall generally not detected. Seasonal results are more signficiant, with drier winter and wetter summer trends throughout.

04 – Interpretation and Conclusion

These results are strong evidence of expanding tropical influences over this region. This is linked to the ongoing expansion of the Hadley Cell poleward. Models in literature attempting to replicate the observed expansion can only do so under increasing sea surface temperatures and greenhouse warming.



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***Abstract*—In Australia's south-west, a warming climate has coincided with decreased precipitation and with runoff decreasing dramatically by up to 70% in the past 50 years. In the south-east, however, these changes are less conspicuous as temperatures have reportedly declined by 0.5°C during the 20th century but there is suggestion that temperatures have since risen. This study has observed the streamflow and rainfall changes in several river regions over New South Wales, Victoria, South Australia, and Tasmania.**

The annual streamflow results show significant reductions over the long-term, particularly with decreasing peak flow values. Rainfall data helps shed light into why this is occurring as changes in precipitation will result in a streamflow response 2.0–3.0 times the magnitude. Though long-term trends in the annual precipitation data were not compelling, there were notable changes between the seasons. Mirroring the results in Western Australia, the summer seasons are now wetter, graduating towards the northern, sub-tropical regions where summer rainfall is dominant. Meanwhile, the autumn to winter period are drier in the southern, temperate regions dominated by cool-season rainfall. These seasonal shifts are observed and amplified in the streamflow values. However, there is difficulty in assessing whether the origin of the changes is climatic, or due to changing land use within the catchment.

The link between the results derived in this study and climate change is related to the observed ongoing expansion of the southern hemisphere Hadley Cell polewards. Expanding tropical influences lead to wetter summers, whilst the mid-latitude storm tracks that supply winter rainfall to the temperate zones are pushed further south. Though not as emphatic as the effects observed in the south-west, there is compelling evidence for climate change in the water resources of Australia's south-east.

I. Introduction

Australia as a nation is highly dependent on water resources originating from rainfall. In Western Australia's southwest, water resources have declined severely, especially around Perth where the surface water runoff has decreased by up to 70% over the last 50 years (Munday, Cordery, and Rubinstein, 2013). This is correlated with a 15–20% decrease in rainfall since the 1970s (Petrone et al., 2010). New South Wales is particularly dependent on surface water and Sydney solely relied on dams until the opening of the Kurnell desalination plant in 2010 in response to the record-breaking Millennium Drought that ran from 1997 to 2009. Since then, desalination plants in Adelaide, Perth, the Gold Coast, and in Melbourne have either been constructed or expanded. Whilst the drought has been broken by a historic wet season, the looming threat of climate change has the potential to burden the water supply anew, especially with the cities' rapidly growing populations.

Research into climatic models predict, with significant uncertainty, that by 2030 southeast Australia will experience a 20% decrease in annual rainfall runoff (Chiew and McMahon, 2002). However, from Munday et al.'s research, it is suggested that the data for south-eastern Australia reveals no notable change in water resources and an overall 0.5°C drop in temperatures over the previous century. Whilst the data is readily available, an up to date investigation into the temperature, precipitation and streamflow data of south-eastern Australia has not been undertaken. It would therefore be prudent to conduct such a study of the past century at monthly intervals to determine if there is long term evidence of any climate change impact on the water resources.

II. Literature Review

The challenge of this research lies not in determining if there are long-term changes in streamflow data but isolating what proportion of these changes have climatic causes and determining if these causes can be linked to anthropogenic climate change. The literature in the following sections was invaluable to this study in comparing observed climate behaviours to what is predicted in models, as well as establishing statistical methodology for climate data analysis.

A. Climatic Studies

The study conducted by Munday et al. on Western Australia indicates significant change in the overall hydrologic regimes of the region. Is the decrease in precipitation in the south of the country correlated with dryer winters, and are larger increases in precipitation in the north correlated with wetter summers? The temperature anomaly (difference from the long-term mean) shows an increase across the board since 1900 with temperatures steadily rising between 1°C and 2°C across the state of WA. The most significant increases are present in the mean minimum temperatures. Conversely, the research suggests that the south-east of Australia has experienced a 0.5°C drop from 1900 to 2010. However, the findings in a 2010 report published by the South Eastern Australian Climate Initiative (SEACI), reveal that every year since 1996 has been hotter than the 1961– 1996 mean, indicating a recent warming trend. Rainfall has correspondingly fallen with 1997-2009 the driest 13-year period since 1900.

The findings of the 2010 report are indicative of the Millennium drought which was subsequently broken by a La-Niña event causing the wettest 2-year period on record (2010–2011) (Post et al., 2014). In Post et al.'s research, it is revealed that the drought was caused by dry cool seasons and broken by unusually wet warm seasons. Of notability is that the rainfall was particularly concentrated on the north of the continent which ties back to Munday et al.'s research. These findings may be attributed to the expansion of the Southern Hemisphere Hadley cell. The cell has appeared to expand 0.5°in latitude towards the pole per decade since 1979, shifting the subtropical ridge further south and increasing its intensity. This pushes rainfall further south resulting in dryer cool seasons in south-eastern Australia. This is especially important because most runoff in Australia's temperate zones occurs in autumn and winter. Finally, climate models attempting to replicate this expansion of the Hadley cell only reproduced the observed results when human factors, such as greenhouse gases, aerosols and ozone depletion, were inputted. This cements the role of anthropogenic climate change in the potential decrease of water resources in the region.

A paper by Cai et al. (2014) on the effects of global warming on the ENSO cycle predicts a significant increase in the intensity and occurrence of El Niño events. The study makes reference to two major events, the 1997–98 and 1982–83 El-Niño extremes, which featured an unusually long extension of warm sea temperatures and atmospheric convection, resulting in rainfall increases. The disruption of these convections has global ramifications. The sea surface temperatures and precipitation anomalies are much smaller in these events. The study's forecasts are determined using 20 different Coupled General Circulation Models (CGCM) with control models not accounting for climate change, and ones that account for climate change. Overall, the simulations indicate a slight decrease in the frequency of all El-Niño events, but the incidence of extreme El-Niño events are doubled, with a recurrence of once every 10 years (as opposed to once every 20 years for the control simulations). The reason for this is that under a warmer climate around the equator, more precisely the intertropical convergence zone, it takes a smaller sea surface temperature increase to establish a warm pool in the east pacific.

B. Climate Elasticity

Streamflow elasticity is the responsiveness of streamflow discharge with change in rainfall. This is important to this study because streamflow discharge is not exclusively related to the climate, whilst rainfall changes are numerically subtle but have magnified effects on runoff.

The simplest method is to determine rainfall elasticity, defined as the proportional mean annual change in streamflow divided by the mean annual change in rainfall (Chiew, 2006). In Chiew's research, he estimated the rainfall elasticity from historic precipitation and streamflow data which can be more easily reproduced and justified. A total of 219 catchments across Australia were tested, with a heavy emphasis on the east coast and the southeast. In about 70% of the observed catchments (particularly in the south and east), a rainfall elasticity of 2.0–3.5 was observed. This means that if a 1% change in mean annual rainfall were to be observed, a 2.0– 3.5% change in the mean annual streamflow is to be expected.

C. Human Influence

The removal of human-induced changes to streamflow is the most challenging aspect of this study. The way it is addressed is to obtain information on changes in land-use in the catchments, and constructions of weirs or dams upstream of the discharge measuring points. This will then need to be compared to abrupt changes in streamflow discharge as climatic effects can only happen gradually over long time frames.

Four examples of related studies that have utilised this idea have been conducted in the Zhengshui River Basin (Du et al., 2011), Taoer River (Li et al., 2013), the Luan River Basin (Wang et al., 2016), and the Poyang Lake Basin (Zhang et al., 2016) in China. These four research papers all used the Mann-Kendell trend detection method which is a rank-based method in detecting linear trends, particularly in non-normally distributed data. In the research conducted by Wang et al. (2015) distinguishing climate change and human-induced effects on streamflow was conducted using a change-point analysis with a non-parametric Mann-Kendall test. Abrupt change in trend identified by the change-point analysis correspond with a large historical change in land use. The research conducted by Li et al. (2013) used a *t*-test to detect change points in the data. The reason for the choice in change-point test in either paper is unspecified. A comparative study by Yue and Pilon (2014), compares the power (probability in rejecting a null hypothesis) of different statistical tests. Overall, a *t*-test is more powerful when assuming a non-normally distributed dataset, whilst the converse is true for the Mann-Kendell test.

III. INVESTIGATION

A. Data Sourcing

Of all the hydrological reference stations gathered for this study, a total of seventeen were isolated based on the length and completeness of their data record. The region analysed ranges from the Hunter valley in the north, Adelaide in the west, and northern Tasmania to the south. The stations are representative of fourteen major river catchments, four in New South Wales, six in Victoria, two in South Australia, and two in Tasmania. General information on the hydrological stations is shown in Table I.

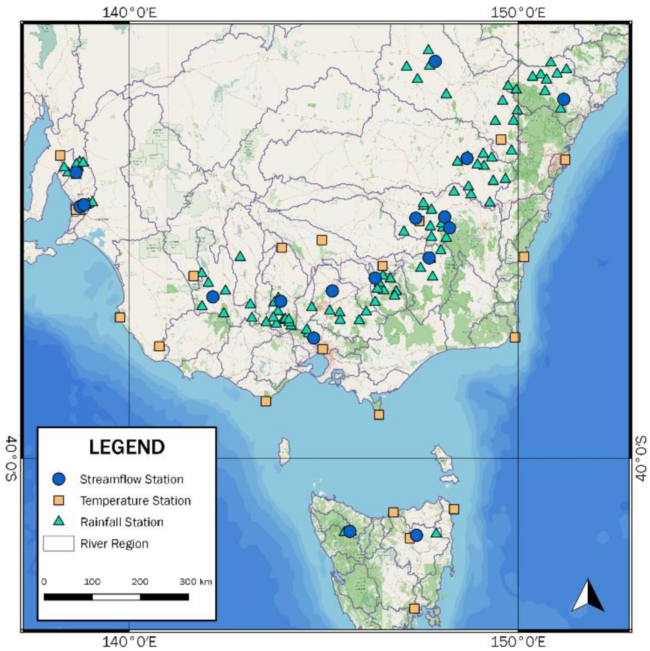
State	Catchment	Station	Record Length (Months)
New South Wales	Murrumbidgee	410001	1489
		410004	1443
		410006	1295
	Lachlan	412002	1397
	Macquarie	421004	1121
	Hunter	210001	1238
Victoria	Ovens	403200	1545
	Loddon	407203	1487
	Maribyrnong	230202	1128
	Wimmera-Avon	415200	1250
	Upper Murray	401201	1485
	Goulburn	405200	1485
South Australia	Torrens	A5040501	924
		A5040508	777
	Wakefield	A5060500	669
Tasmania	Arthur	61	1115
	Tamar	318076	768

TABLE I

SUMMARY OF STREAMFLOW DISCHARGE GAUGING STATIONS USED IN THIS STUDY.

Figure 1 shows the locations of the rainfall, temperature, and streamflow stations over the region used in this study.

Figure 1. South-east Australia showing locations of the meteorological and hydrological stations assessed in this study.



B. Rainfall Results

The figures on the following page show the monthly rainfall trends over the entire region, using the Inverse Distance Weighting (IDW) method on the stations collected for this study. Note that the rainfall stations used are mostly concentrated on the coasts as inland stations are fewer in number and tend to have shorter records. However, climate variability in continental regions is generally lower.

The trends observed are determined using the Theil-Sen slope estimator in the statistics software package R. The first figure shows the trends over the entire rainfall record, from the late 19th century (usually the 1880s) to 2016. The second figure shows the rainfall trends from 1950 to 2016, as most streamflow and some rainfall records detect break points during this time period which indicate a jump to wetter conditions. Note that green to blue areas show increasing rainfall trends, whilst yellow to red areas show decreasing rainfall trends.

Figure 2. Late 19th Century to present rainfall trends mapped with the IDW method.

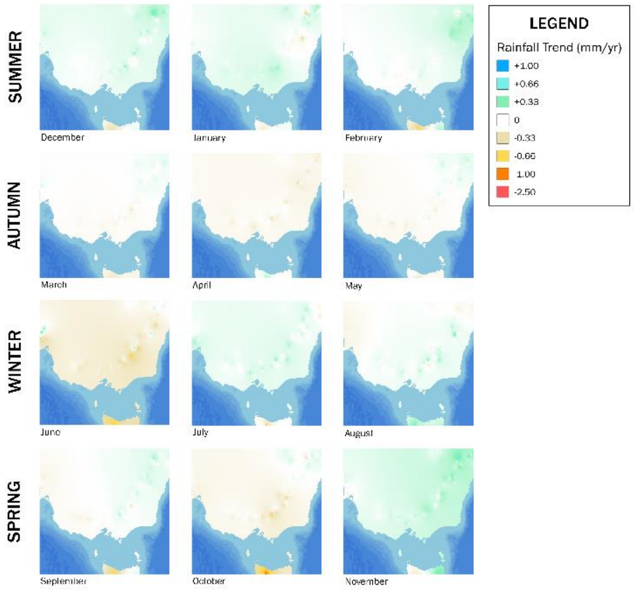
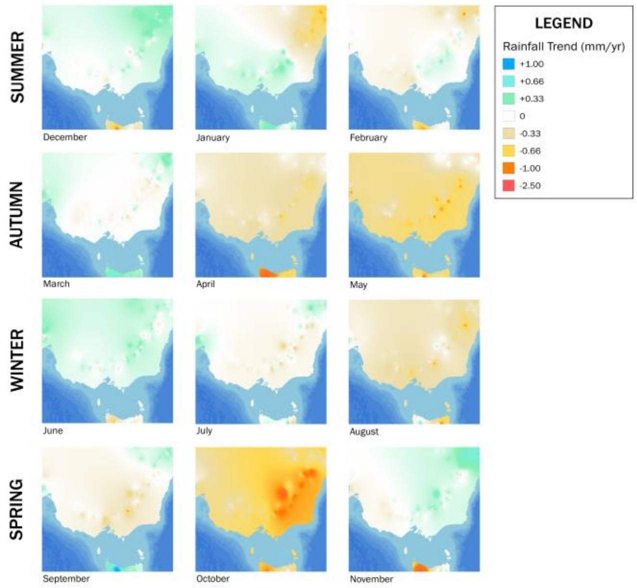


Figure 3. Mid-20th Century to present rainfall trends mapped with the IDW method.



Season	Month	Late 19th Century to Present
Summer	December	General increases, graduating towards the north. Tasmania decreasing.
	January	Increasing trends, particularly in the south. Northern trends less significant, with some areas stable. Tasmania decreasing.
	February	General increases, particularly in the north.
Autumn	March	Mostly stable. Slight increases in the north and decreases in the south and Tasmania.
	April	Slight decreases throughout. Tasmania slight increases.
	May	Slight decreases throughout most of the region, with slight increases in the north.
Winter	June	Decreases throughout.
	July	Increases throughout. Decreases in Tasmania.
	August	Increases in the south and Tasmania. Decreases in the north and west.
Spring	September	Increases in the north and along the east. Decreases in Tasmania and the west.
	October	Decreases throughout the region. Slight increases in the extreme norths.
	November	Increases throughout.

TABLE II

DESCRIPTION OF THE LATE 19TH CENTURY TO PRESENT MONTHLY RAINFALL TRENDS DISCOVERED BY THIS STUDY, PRESENTED IN FIGURE 2.

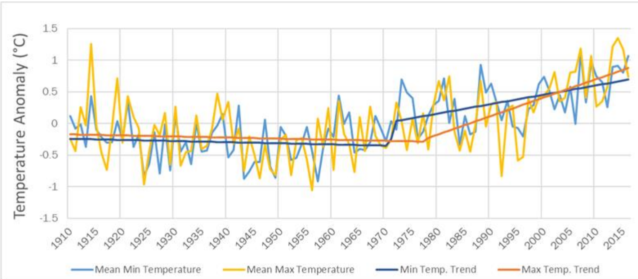
Season	Month	Mid-20th Century to Present
Summer	December	Same as the long-term trend but more significant in both trends.
	January	Increasing trends in the south. Decreasing trends graduating towards the north.
	February	Decreasing trends throughout except for increases around the south-east of Victoria.
Autumn	March	Slight decreases in the south. Increases in Tasmania, extreme north, and west.
	April	Decreases throughout, particularly significant in Tasmania.
	May	Decreases throughout.
Winter	June	Increases throughout. Tasmania slight decreases.
	July	Decreases throughout, with slight increases in the extreme north and west.
	August	Decreases throughout.
Spring	September	Decreases throughout. Increases in the north. Significant increases in Tasmania.
	October	Severe decreases in the entire region.
	November	Increases throughout. Steady to slight decreases in the west and south-west. Significant decreases in Tasmania.

TABLE III

DESCRIPTION OF THE MID-20TH CENTURY TO PRESENT MONTHLY RAINFALL TRENDS DISCOVERED BY THIS STUDY, PRESENTED IN FIGURE 3.

C. *Temperature Results*

Figure 4. Temperature anomaly throughout south-east Australia with Sen slopes before and after the 1970s break point.



Though not a primary concern of this study, temperature data from the stations shown in Figure 1 was gathered to update the temperature trend over this region to 2016. As shown in Figure 4 the annual temperature anomaly (difference from long- term mean) has risen sharply since the 1970s. Non-parametric analyses conducted on the data identify that the decreasing trend observed up to the 1970s is not statistically significant in either of the series. Ordinary least squares analysis built into Microsoft Excel reproduces a near-identical result to the Theil- Sen slope. From 1910 to 2016, mean minimum temperatures and mean maximum temperatures have risen by 0.7°C and 0.9°C respectively.

IV. Discussion

A. *Summary of Results*

The evidence presented in this study proves there are indications of climate change within water resource data in Australia's south-east. Seasonal shifts in precipitation are notable, particularly towards the south, and these are reflected in the streamflow response. Although streamflow data is influenced by factors other than the climate, the fact that these behaviours are consistently observed throughout the region strengthens the argument that at least a portion of these changes are climatic in nature.

The streamflow results of this study are generally more persuasive than the rainfall results. This is to be expected as minor changes in rainfall translate to larger changes in runoff, as already discussed. The trend tests for streamflow generally show decreases over the long term, particularly in the southernmost and inland catchments. There were some increasing long term trends in catchments tending towards the coastal regions near the Alps. However, in nearly all catchments, there were break points detected in the middle of the 20th century (typically between 1947 and 1959). Most of these mid-century records indicate a decreasing trend, and most are statistically significant. These increases are indicative of the cooler, wetter climate that is observed in south-eastern Australia from the end of the 19th century to around the 1950s. Where these break points are detected in streamflow, they are also reflected in the precipitation records of their respective catchment. In summary, the trend tests suggest annual decreases in streamflow from the 1950s to the present. Rainfall trends are occasionally observed but are not considered statistically significant.

The two-sample tests are more convincing, however. They universally show decreases in variance in streamflow. As variance is a measure of spread in data, this is indicative of a reduction in peak flow values. The catchments that showed increasing long-term trends in the trend tests, are also showing decreases in the most recent years, indicating that their discharges are not only returning to the drier conditions of the late 19th century, but may also end up even drier. Rainfall results are similarly not statistically significant but show decreases in most catchments, particularly in the south.

Whilst the annual results may not be particularly convincing taken on their own, the seasonal analysis demystifies the results. What they reveal is that although annual changes in rainfall are undetected, changes between seasonal rainfall are dramatic and it is within this interseasonal variability that runoff has changed.

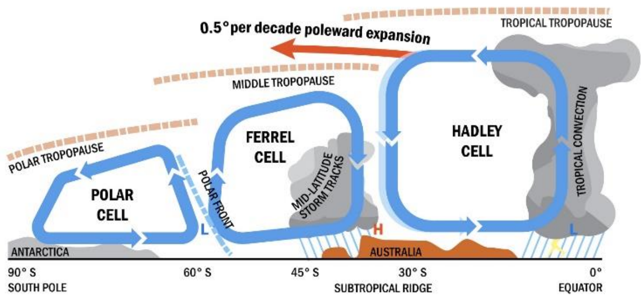
Throughout the region, summers have become increasingly wetter, whilst winters have become drier. It is this offset between summer and winter that has caused the rank-based tests to detect no changes in rainfall over time. However, these changes do not offset each other in magnitude. That is to say, in a temperate region that is dominated by winter rainfall, a proportional decrease in winter rainfall results in a larger deficit of runoff than what can be recouped by a surplus in summer rainfall. This is the reason why the southernmost catchments in the temperate regions show widespread reductions in streamflow. This seasonal shift is an indicator of tropical climate influences expanding southwards. The most noteworthy results in this study are the exceptionally strong drying trend in October rainfall, and the long-term drying trend in June against the anomalous increasing trend since 1950.

What's important to note about these results is that the most dramatic streamflow changes (e.g. Murrumbidgee) exhibit climate elasticity values far exceeding the 2.0–3.0 range derived in literature, which indicate that not all the changes are due to rainfall. The challenge of assessing streamflow changes is that water regulations and diversions, such as the release of flows for irrigation during dry seasons, tend to exaggerate the expected result in these catchments. Yet, rainfall is changing, and in catchments where land use is unlikely to have any impact (e.g. Ovens) these seasonal changes are still observed.

B. The Link to Climate Change

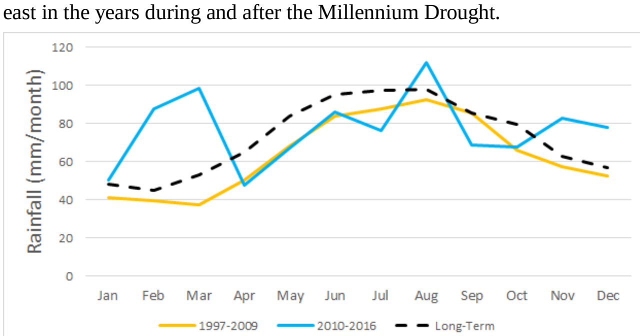
The Earth's atmospheric circulation follows a fairly constant structure, with three circulation cells in each hemisphere. The primary cell is the Hadley cell, named after George Hadley, where air rises at the Intertropical convergence zone at the equator and flows polewards until descending at the subtropical ridge. South-eastern Australia is located below this descending limb of the cycle, with the temperate zone lying south of it, and the subtropical zone lying north.

Figure 5. A diagram of the atmospheric circulations in the southern hemisphere.



The Southern Hemisphere Hadley cell naturally oscillates between the seasons, shifting north during the winter, and south in the summer. Summer warms the air at the equator and causes it to rise. As the ascending air cools, the moisture that is carried in the air condenses and falls as precipitation causing tropical zones to have their wet seasons in the summer. By the time the air descends at the subtropical ridge, most of the moisture has already fallen. This is why the subtropics are dry, with most of the world's deserts located at these latitudes. The interaction of the descending limb of the Hadley cell and the Polar cell causes the mid-latitude regions to be turbulent and these localised pockets of high and low pressure cause the mid-latitude storm tracks. As the Hadley cell shifts northwards in the winter, these storm tracks bring forth the rains in Australia's temperate regions.

Figure 6. Monthly rainfall distribution over Australia's temperate south-east in the years during and after the Millennium Drought.



Research over the past three decades has revealed an overall expansion of the cell since the middle of the 20th century with statistical significance noticed from 1968. Post et al. (2014) suggest that the millennium drought is evidence of this expansion of the southern hemisphere Hadley cell towards the pole. The reason for this is that the drought was a cool season phenomenon, whilst the breaking of the drought in the 2010–12 La Niña episode was a warm season phenomenon. This is evident in figure 6 that shows the monthly rainfall distribution during and after the drought over the catchments analysed in this study (excepting the Hunter and Macquarie as they exhibited tropical behaviours). This is a particularly important distinction as it reveals that the Millennium drought is a symptom of climate change, and not an isolated incident that would otherwise skew the data in favour of a positive result.

V. Conclusion

This study has produced compelling evidence for climate change in Australia's south-eastern water resources. The reduction in stream discharge throughout the region is at least partly caused by seasonal changes in precipitation. In general, and particularly in the temperate zones, summer rainfall has increased, whilst autumn to winter rainfall has decreased indicating an expansion of tropical climatic behaviour southwards. This is undoubtedly linked to and reinforces the findings of much research into the expansion of the southern hemisphere Hadley cell.

The changes observed in most stations far exceed what can be attributed to climatic influences, especially under parametric analyses. However, even between sharply changing discharge behaviours, steady underlying trends can be extracted from the data. The limitations of this study, and in studying streamflow in general, is accounting for how human influences on the river and catchment system can affect the record. As demonstrated in this study, drawing a definitive conclusion and quantifying these effects is difficult and requires care.

This study is merely the first step in understanding climate change's effect on water resources in this region. Future avenues for furthering this research are abundant in order to solve its limitations. Most importantly, a better understanding of how dams affect streamflow records needs to be developed to set a precedent for future studies. Another avenue for research is quantifying the effect of potential evapotranspiration over this region now that temperatures seem to be increasing over time.

The findings presented in this paper first and foremost emphasise the importance of understanding water resources and how their availability may change in the future.

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