Application of Machine Learning Techniques to Detect and Understand the Impacts of Global Warming on Southeast Australia.

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Abstract: Australia is adversely affected by global warming (GW), as its well-known cycles of droughts, floods and extreme weather events are increasingly amplified by GW. Here the focus is the impacts of GW on populous southeast Australia. Machine Learning attribution techniques have been applied to identify the main drivers of these impacts. Examples are presented of the detection of the most relevant drivers, individually and in combination, responsible for observed trends in precipitation and temperature due to GW.

Climate extremes

Australia is a land of climate extremes and southeast Australia experiences extremes of both rainfall and heat. The International Panel on Climate Change (IPCC) average temperature projections routinely are higher than the rest of the world. They have already reached 1.48^{O}C above pre-industrial level and now possibly will reach 2.0^{O}C before 2050. This article focusses on southeast Australia as it is by far the most populous region, with the three largest, coastal, cities of Sydney, Melbourne, and Brisbane (Figure 1) accounting for about 45% (12 million) of the total Australian population (twenty-six million). Away from the coast, the inland portion of southeast Australia, encloses the two most important river systems, the Murray, and Darling Rivers, which are fed by many smaller rivers and streams, together comprising the Murray-Darling Basin (MDB) (Figure 1). The MDB is referred to as the 'bread-basket' or 'food-bowl' of Australia. The MDB occupies just 14% of the Australian land mass but produces 40% of its agricultural produce, including rice (100%), grapes (74%), dairy (30%) and cotton (90%).

Figure 1. Map of southeast Australia. Southeast Australia is divided into coastal and inland areas. The coastal region includes the major cities of Sydney, Brisbane and Melbourne and the inland region consists of the Murray-Darling Basin.

Droughts and Floods

The MDB rivers within southeast Australia have experienced highly variable water flows, following both drought and flood periods. Notably, the 34 months from January 2017 to October 2019 were the driest on record in the MDB and were preceded by years of below average rainfall. The environmental and ecosystem consequences have been striking. Most consequential and visible were the zero-flow events in the Darling River and its tributaries. These zero-flow events resulted in up to one million native fish dying in 2019 in the Darling River, due to the lack of oxygenated water because of algae forming in the warm water of shrunken river waterholes. In the recent extreme flood rains from 2020-2022, the impact was even greater in early 2023. An estimated twenty million native fish died because of heated, contaminated, and de-oxygenated floodplain water flowing back into the river. More fish died following the wet period than in the preceding dry period because the favourable spawning environment in the flooded river system caused a huge increase in the fish population.

Figure 2. Darling River western New South Wales February 2022 where up to twenty million native fish died. The river water was rendered unsuitable for consumption and a major community and government effort was required to remove the dead fish from the river.

Adding to the severe drought, the unregulated extraction of water for irrigation upstream has decreased the water availability. Floods are a normal, though infrequent occurrence to which river ecosystems have adapted. However, the implementation of ‘floodplain harvesting’, which is a process of storing floodplain water in privately owned dams instead of allowing it to flow back into the river system also has reduced river flows at times when floods are not occurring.

Fires and Floods

Drought and extreme heat leading up to the 2019/20 summer (December-February) resulted in deadly bushfires in southeast Australia. The fires impacted both inland and coastal parts of southeast Australia. The drought also led to fuel-moisture deficiency and during heatwaves these conditions led to the uncontrollable fires of 2019/20, which were worsened by shortened time periods in which to conduct the routine management practice of prescribed burning prior to the fire season. Moreover, the shortened cool season in southeast Australia resulting from GW, allowed less time for the prescribed burning to be carried out. In remote inland locations, water brought in by road transport for human consumption was a frequent practice because many dams and river levels were either very low, highly polluted, or both.

Like many other parts of the world that have marginal, and highly variable, annual rainfall totals, in Australia drought conditions can quickly switch to flood events. Severe to extreme flooding occurred along the coast of southeast Australia during the period 2020 to 2022. After rain had steadily filled inland and coastal river systems during those years, in February 2022 the biggest flood in modern day Australian history occurred south of Brisbane in the small but important city of Lismore. Over a period of four days leading up to the disaster, three rain episodes occurred. Under usual conditions each would have generated a moderate flood, but cumulatively they generated river heights in Lismore that broke the previous record by 2.2 metres. Subsequent human deaths resulted from drowning because many of the inundated houses were built on the exposed flood plain. The main local government, business and shopping areas of the city could not cope with the amount of water that entered downtown Lismore. The residents of Lismore routinely prepare for anticipated flood heights experienced in previous floods. However, the record-breaking flood height in February 2022 was an extreme outlier of 14.4 m (Figure 3).

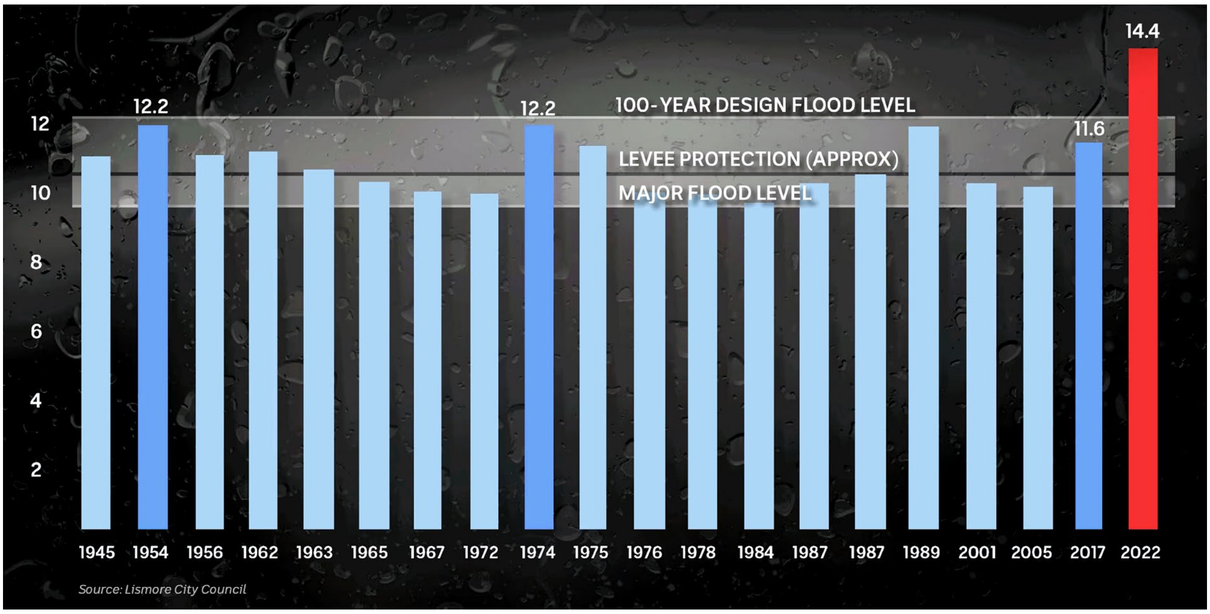

Figure 3. History of flood heights (metres) on the Wilson River Lismore showing, on the far right, the extreme outlier of 14.4m that occurred during the February 2022 flood.

In anticipation of future occurrences of even more extreme flood events, adaptation requires strict planning controls in this area and further south along the coast, including Sydney where a substantial portion of the population also has expanded onto the flood plains. The temporal characteristics of southeast Australian rainfall have changed in recent decades on most periods, including daily, monthly, and annual timescales. For example, in 2022 Sydney broke its official October rainfall record and its annual rainfall record was broken before the end of October, after more than 150 years of official observations. The new annual record rainfall for Sydney was 2600mm (or 104 inches), more than double the long-term annual average of around 1200mm (48 inches). Furthermore, the longest dry period on record in southeast Australia from 1997 until 2009 became known as the Millennium Drought, which was then followed by a very wet period from 2010-2012 that produced extreme rainfall and floods in various parts of southeast Australia in addition to deaths from catastrophic flooding in southeast coastal areas. Daily and monthly record rainfall totals were set in inland Queensland during 2022.

Southeast Australian Climate Drivers

The development of novel statistical techniques over the past decade or so included Machine learning (ML) techniques. Such techniques were ideally suited for application to rainfall and temperature data to reveal important climate drivers over southeast Australia, both individually and in combination with other climate drivers, in response to GW over recent decades. A range of ML techniques that have proven to be effective in uncovering attributes in what can be described as "forensic meteorology" have found strong links with four main Australian climate drivers. The identified climate drivers include both the El Nino Southern Oscillation (ENSO) and the Indian Ocean dipole (IOD, which are ocean climate drivers and the atmospheric climate driver, the Southern Annular Mode (SAM), together with increasing warming trends in local and global atmospheric temperatures and in oceanic sea surface temperatures. The ML techniques that were successful in detecting strong signals in those climate drivers include both linear and nonlinear regression methods, with the nonlinear methods typically proving to be more successful than the linear regression (LR) approaches. The nonlinear methods used by the authors included Support Vector Regression (SVR), Random Forests and Artificial Neural Networks (ANN). It is planned to extend the ML methods to a variety of Deep Learning approaches in future studies. Also planned are hybrid techniques, combining ML and numerical climate model projections.

Application of ML to extreme events in southeast Australia

There is a rise in the growth of Artificial Intelligence (AI) and Machine Learning (ML). ML methods have proven to be well-suited for the data mining of rainfall and temperature archives. ML is also valuable in revealing climate drivers and including their combinations which impact southeast Australia the most in the study of "forensic meteorology." The ML techniques most successful in detecting strong GW correlations with those climate drivers include both linear and nonlinear regression methods, with the latter typically proving to be more effective. The authors used nonlinear methods, including SVR, and Random Forests.

The ML techniques used in climate and weather attribution applications mostly employ supervised ML, although unsupervised ML techniques are increasingly being explored. Supervised ML involves creating algorithms that "learn" the links between input and output data. In climate and weather applications, the input data are observed variables such as temperature, precipitation, etc., for a specified time period, and the output data are the observations from a different time period, usually a period in the future when ML is deployed for predictions. The model identifies the combinations of climate drivers that provide the best explanation for the relationship between data from the two time periods, a technique referred to as regression. Those climate drivers found to be statistically significant can then be used to understand the factors influencing changes in the observed climate variables.

To illustrate the utility of ML in the identification of those climate drivers responsible for the increasing extreme climate and weather occurrences, we applied ML to a selection of two extreme events: a drought and a heat wave, both of which affected southeast Australia and were made far more likely by the accelerated GW trend since the early 1990s.

ML application to a drought in the MDB

Continental southeast Australia lies within the subtropics. Historically, it has been influenced by both mid-latitude and tropical climate factors. The northern part of the MDB (approximately between 25^{O}S to 30^{O}S) exhibits high annual rainfall variability because it is located near the equatorward-most limit of the mid-latitude influence during the cool season (April-September) and then in the warm season (October-March), relies mainly on the tropical ENSO influence of a positive La Nina phase to boost warm season rainfall. From forty-five potential climate predictors, ML regression strongly suggests that the ocean and atmospheric climate drivers related to ENSO have been the main influence on spring/summer rainfall in this inland area between 25^{O}S and 30^{O}S in combination with the southern annular mode (SAM). In its positive phase SAM enhances atmospheric moisture from onshore wind flow. Notably, in addition to spring/summer, for other periods throughout the year, the selected attributes are all related to GW, global temperature, global sea-surface temperature anomalies and Tasman Sea sea-surface temperature anomalies.

In recent decades, the city of Canberra, which is in the southern inland part of the MDB, has shown no trend in annual rainfall. A decrease in autumn rainfall is compensated by a slight increase in spring/summer rainfall, which results in no annual rainfall trend. Mean maximum temperature, on the other hand, shows a steady increase in recent decades. Drought is becoming more frequent and more severe as the mean maximum temperature increase leads to increased evaporation and the bushfire threat. ML was used to model annual rainfall and mean maximum temperature to highlight the most important climate drivers because it can prove useful information to manage future water resources. It was found that the annual rainfall attributes included the IOD, SAM, the southern oscillation index (SOI), and Tasman sea-surface temperature anomalies. The IOD and measures of GW are mostly influenced by annual mean maximum temperature. As a result, the main finding from this study is that rainfall and temperatures are evolving in a way that decreases catchment inflows and increases the likelihood of drought in Canberra. Therefore, as the Canberra population continues to increase, demand on water resources also is expected to increase.

In the recent accelerated GW period which, for Australia, is approximately the 30-year period since the early 1990s, areas of southeast Australia are becoming increasingly affected by both severe droughts and flood-producing rains. There are numerous factors that influence the severity of droughts over time, including temperature and land surface changes, increases in potential evapotranspiration, higher wind speeds and reduced humidity. Wide ranging impacts occur on the built and natural environment including increased bushfire threat and flooding risk from runoff when rain falls on dry soil, reducing agricultural yields and inducing negative mental health effects. Many of these effects have occurred across both coastal and inland southeast Australia during the most recent drought (2017-2019) when widespread, intense wildfires during the 2019-2020 summer affected much of the region. The fires were followed by flooding rain events during 2020 to 2023. Sydney recorded rapidly decreasing dam water storage during 2019 and the lowest inflows on record, which led to strict water usage rules. In contrast, as mentioned above, Sydney's 2022 October rainfall record was broken after more than 150 years of observations and the 2022 annual rainfall was broken halfway through October. Our ML models developed for the Sydney catchment rainfall revealed attributes that involved clear links between climate driver indices and annual, autumn and winter rainfall.

ML application to an urban heat island

On a much smaller scale than the MDB, we have used ML techniques to investigate the increasing difference between mean summer maximum temperatures in the coastal suburbs of Sydney compared with those in the inland western suburbs of the Sydney metropolitan area. Western Sydney currently experiences far more intense summer (defined as December – March) heatwaves than coastal Sydney with maximum temperatures exceeding those of coastal Sydney by up to 10^{O}C. In addition to escalated bushfire danger, extreme temperature days pose health and socio-economic threats to western Sydney, together with creating longer summers, shorter winters, and hence decreasing time frames for implementing bushfire management strategies. Western Sydney has a higher unemployment rate than coastal Sydney and has the highest proportion of low-income families in the Sydney region. GW is expected to worsen the already large socio-economic divide between coast and western Sydney and push more people into poverty. As GW impacts increase, some western region areas are trialling evacuation shelters to mitigate growing heatwave risks. Two-thirds of the population growth in entire Sydney metropolitan area, by 2036, is projected to occur in western Sydney. Such an increase in population requires extensive infrastructure development and a growing economy, one which is set to be impacted by extreme temperatures. For example, extensive housing development is currently not accompanied by adequate shading to help mitigate the effects of extreme heat days (Figure 4).

Figure 4. Example of housing development exposed to the sun in western Sydney. Prior to land clearance before development, the region consisted of shaded, dry sclerophyll forest.

Hence, there is an urgent need to understand how Sydney's western suburbs differ from near-coastal suburbs in terms of temperature as well as determining the factors that contribute to these differences. Our recent research highlights a growing interest in understanding the roles of Australian region climate drivers, particularly GW, in influencing these changes. We obtained the attribution of observed maximum summer temperatures at western and coastal Sydney applying ML techniques, described above, to the known climate drivers. We found a marked disparity in the percentage of summer days above the 95th percentile during the accelerated climate change period (1992-2021) between western Sydney (+35%) and coastal Sydney (-24%), relative to 1962-1991. The climate drivers detected as attributes were similar for both coastal Sydney and western Sydney but, as expected, coastal Sydney was more affected than western Sydney by oceanic climate drivers.

Conclusions

The attribution techniques we have developed provide a deeper understanding of the complex relationships between climate indices and atmospheric variables. This knowledge can assist in identifying those climate drivers used in seasonal forecasts of atmospheric variables such as precipitation and temperature, which are performed by national weather agencies including the Australian Bureau of Meteorology, UK Met Office, and the USA National Weather Service. The knowledge gained from the above studies has highlighted the importance of testing a wide range of ML techniques when developing a statistical model, rather than assuming that there is a single best approach.

Our ML work identified attributes for regions of southeast Australia, revealing that the observed trends in climate and extreme events have been driven by accelerated global warming (GW) of the atmosphere and oceans. Importantly, we found that GW is modulated by the various phases of the various climate drivers affecting southeast Australia. These modulations can amplify, lessen, or have a neutral effect on the impacts of GW. In the period 2017-2019, the impact was dominated by drought (and its many consequences), culminating in the record fire season of late 2019/early 2020. Then, changes in the climate driver phases produced the wet conditions of 2020-2022, this time generating some of the most extensive floods ever recorded in southeast Australia.

Notably, as we write this GJIA article, 2023 has seen a switch in the phases of key climate drivers, most notably the Indian Ocean Dipole and ENSO, with a consequent rapid return to the dry conditions that were present in the decades prior to 2020-2022. Many record-setting low cool season rainfall totals have occurred, together with abnormally high temperatures. River levels in the Murray Darling Basin are again experiencing low flows and the massive fish deaths have returned. The seasonal outlook for the coming summer months suggests strongly that the drought will worsen in the agricultural areas and the fire season will be earlier and severe.

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