Numerical and Statistical Modelling of Australian Severe Weather

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Joshua Hartigan declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mathematical and Physical Sciences at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

Various forms of severe weather frequently impact communities around Australia, including drought, floods, bushfires, severe convective thunderstorms and tropical cyclones. Such events have varied temporal scales and can have a significant effect on society, especially when multiple events occur shortly after each other or at the same time. As the global warming trend continues, the threat of severe weather impacting regions likely will change. Along with using global circulation models and regional climate models to understand how future warming will affect the risk of severe weather, it is important to study severe weather historically, and trends in severe weather and related variables, as this highlights the performance of modelling efforts, and what is currently occurring. Additionally, statistical modelling can be used to assess the attributes of severe weather, at the time scales important to forecasting and planning for these events. However, non-linear statistical methods including machine learning have seldom been used in the atmospheric and climate sciences to help understand severe weather, especially in Australia. Meanwhile, numerical modelling can be applied to past events, such as severe convection, to help understand how the event developed and improve future forecasting of similar events. Yet, there are few numerical modelling case studies of severe convective storms in Australia, particularly for tornadic storms, with much of the knowledge Australian forecasters rely on coming from studies and understandings developed overseas. This thesis applies trend analysis and statistical modelling to improve understanding of drought across southeast Australia, and severe convective storm hazard environments across Australia. Numerical modelling also is applied to a case study of a tornadic storm in Australia's most populous city, Sydney.

First, trends in drought are understood through analysis of change to percentiles, bootstrap resampling of periods within the time series, and permutation testing to understand statistical significance. This has been applied to key areas in southeast Australia, including the Hunter Valley Region, Sydney Catchment Area (SCA), Canberra city, and the Northern Murray-Darling Basin. It was found that, overall, there are concerning changes to precipitation mean and variance particularly over the cool season, suggesting a reduction in streamflow across the region. Coupled with increasing mean temperatures for most seasons across southeast Australia causing an increase in potential evapotranspiration, there appears to be a trend towards more frequent and severe drought. Wavelet analysis was applied to assess potential climate drivers within the time series, and how the relationships with these climate drivers have changed over time. Finally, statistical modelling was applied to further understand the key climate drivers associated with precipitation in the region, and assess how well different modelling techniques perform on prediction over the climate-scale. These models generally performed better than the climatology, and highlighted the influence of global warming on precipitation with Tasman Sea Surface Temperature Anomalies a frequently selected attribute. This is particularly apparent in the SCA, where models performed particularly well on predicting annual precipitation, despite trends in the time series.

On 16 December 2015, a severe thunderstorm and associated tornado affected Sydney, causing widespread damage and insured losses of $206 million. This storm severely impacted the suburb of Kurnell, with significant damage sustained to Sydney's desalination plant, which supplies up to 15% of Sydney water during drought. High resolution numerical simulations of this storm were conducted using the Weather Research and Forecasting (WRF) model on a double nested domain using ECMWF's ERA5 reanalysis data for initial conditions. The results from simulations with the Morrison microphysics scheme are compared to those from the National Severe Storms Laboratory double-moment 4-ice microphysics scheme. Both simulations produced severe convective storms that followed similar paths to the observed storm, but the Morrison scheme did not display the same morphology. On the other hand, the storm simulated with

the NSSL scheme displayed cyclical low- and mid-level mesocyclone development, which was observed in the Kurnell storm. This highlights how supportive the atmosphere was for development of severe rotating thunderstorms with the potential to produce tornadoes. The work presented in this thesis displays the applicability of the WRF model to studying the causes of high-impact Australian thunderstorms.

In the final part of this thesis, statistical modelling is applied to better understand the atmospheric variables most closely associated with severe convective storm hazards (i.e., hail over 2 cm, wind gusts above 90 km/hr or tornadoes). The best performing models were then applied to the Bureau of Meteorology's BARRA reanalysis data set. This highlighted differing regions of Australia that are most likely affected by the individual hazards. There was a high frequency of hail environments over eastern Australia, particularly from the central coast of NSW into southeast Queensland, and the far southeast of Australia. There is a similar peak in the frequency of tornadic environments, with an additional high frequency of environments across much of southern Australia, likely due to cool-season tornadoes. Meanwhile, for environments supportive of severe convective wind, there was a high frequency of environments over part of eastern Australia. There was a very high frequency of environments for all three hazards over much of northern Australia. This is suggested to be an overestimation, except possibly for wind environments, as the majority of data that the statistical models were trained on, was obtained from the southeast of Australia. For wind environments, there were more reports in northern Australia, so the model is likely better trained to assess environment frequency across both regions. These results highlight the importance of developing a spatially balanced data set, along with categorically balanced data, or otherwise breaking a large area into smaller regions, prior to training statistical models. Spatial changes in the frequency of severe thunderstorm hazard environments were assessed between two periods in the BARRA data set. It was found that hail and tornadic environments have increased in frequency over eastern Australia during spring, tornadic environments have also increased in frequency over southeast and northwest Australia during summer, while they have decreased over southwest Australia during autumn and winter. There also is an increase in the frequency of environments supportive of severe wind thunderstorms over Western Australia and eastern Australia during spring, and parts of southwest and southeast Australia during summer.

Supporting Publications

Hartigan, J., MacNamara, S., and Leslie, L.M. Comparing precipitation and temperature trends between inland and coastal locations. ANZIAM J, 60:C109–C126, 2018. DOI: 10.21914/anziamj.v60i0.13967

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Hartigan, J., MacNamara, S., and Leslie, L.M. Application of Machine Learning to Attribution and Prediction of Seasonal Precipitation and Temperature Trends in Canberra, Australia. Climate, 8(6):76, 2020. DOI: 10.3390/cli8060076

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Speer, M.S., Hartigan, J., and Leslie, L.M. Machine Learning Assessment of the Impact of Global Warming on the Climate Drivers of Water Supply to Australia's Northern Murray-Darling Basin. Water, 14(19):3073, 2022. DOI: 10.3390/w14193073

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Abbrevations

- AMO: Atlantic Multidecadal Oscillation
- ARW: Advanced Research WRF
- BARRA: Bureau of Meteorology Atmospheric Reanalysis
- BoM: Bureau of Meteorology
- CAPE: Convective Available Potential Energy
- CIN: Convective Inhibition
- DMC: Deep Moist Convection
- DMI: Dipole Mode Index
- ECMWF: European Centre for Medium-Range Weather Forecasts
- EHI: Energy Helicity Index
- EL: Equilibrium Level
- ENSO: El-Niño Southern Oscillation
- GLD360: Global Lightning Dataset 360
- GlobalSSTA: Global Sea Surface Temperature Anomalies
- GlobalT: Global Temperature Anomalies
- GRIB: General Regularly Distributed Information in Binary form
- IOD: Indian Ocean Dipole
- IQR: Interquartile Range
- IPO: Interdecadal Pacific Oscillation
- JJAS: June, July, August, September (the southern Australian cool season)
- LapR: Lapse Rate
- LCL: Lifted Condensation Level
- LFC: Level of Free Convection
- LI: Lifted Index
- LR: Linear Regression
- LogR: Logistic Regression
- LSM: Land-surface model
- MATLAB: MATrix LABoratory
- MCS: Mesoscale Convective System

- MDB: Murray-Darling Basin
- MESH: Maximum Estimated Size of Hail
- ML: Mixed-Layer
- MSE: Mean Square Error
- MU: Most-Unstable
- NMDB: Northern Murray-Darling Basin
- NSSL: National Severe Storms Laboratory
- NSW: New South Wales
- OT: Overshooting Cloud-Top
- PBL: Planetary Boundary Layer
- PDO: Pacific Decadal Oscillation
- Poly: Polynomial kernel
- PW: Precipitable Water
- QLCS: Quasi-Linear Convective System
- RBF: Radial Basis Function kernel
- RF: Random Forest
- RK3: Runge-Kutta third-order integration scheme
- RMSE: Root Mean Square Error
- RSS: Residual Sum of Squares
- S06: 0–6 km bulk shear
- SA: South Australia
- SB: Surface-Based
- SAM: Southern Annular Mode
- SCA: Sydney Catchment Area
- SCP: Supercell Composite Parameter
- SCT: Severe Convective Thunderstorm
- SD: Standard Deviation
- SHERB: Severe Hazards in Environments with Reduced Buoyancy Index
- SHIP: Significant Hail Parameter
- SOI: Southern Oscillation Index

- SRH: Storm-Relative Helicity
- STA: Severe Thunderstorm Archive
- STP: Significant Tornado Parameter
- SVM: Support Vector Machine
- SVR: Support Vector Regression
- SWEAT: Severe Weather Threat Index
- TMax: Mean maximum temperature
- TMin: Mean minimum temperature
- TPI: Tripole Index for the Interdecadal Pacific Oscillation
- TSSST: Tasman Sea Sea Surface Temperature Anomalies
- TT: Total Totals
- UK: United Kingdom
- USA: United States of America
- UTC: Universal Coordinated Time
- VWS: Vertical Wind Shear
- WA: Western Australia
- WRF: Weather Research and Forecasting