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EXAMINING THE USE OF TROPICAL CYCLONE GENESIS INDICES IN PRESENT AND FUTURE CLIMATE FOR THE SOUTH PACIFIC BASIN

by

Alick Haruhiru

A thesis submitted in the fulfillment of the requirements for the Degree of Masters of Science in Climate Change

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Pacific Centre for Environment and Sustainable Development
Faculty of Science, Technology and Environment
The University of the South Pacific

July 2015
Declaration

A Statement by the Author

I, Alick Haruhiru, declare that this thesis is my own work and that, to the best of my knowledge, it contains no material previously published, or substantially overlapping with material submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Alick Haruhiru (S11026324)
Date……09/09/2015……….

A Statement by the Supervisor

The research in this thesis was performed under my supervision and to my knowledge is the sole work of Alick Haruhiru.

Professor Elisabeth Holland
Principal Supervisor
Date…..08/09/2015……. 
Dedication

This thesis is dedicated to two key people who initially inspired me to highly value education and make the most of all the opportunities I have to study. Emphasizing the essence and importance of formal education was the most frequent advice my father gave his children. His words were like those from a person who had a formal education with at least a single certificate or someone who is benefiting from being educated. I trust that encouragements about the value of education from my father, who never had any formal education, have helped me progress this far.

Furthermore, I dedicate this work to my uncle for his investment in my education career from high school to my scholarship year. Because he earned both undergraduate and graduate certificates, his support and advice motivates me to progress to the postgraduate level.

Every time I faced challenges throughout this project, I always recalled their encouragements and advice as memorial words and souvenirs. That was what kept me going!

With that, I wish to dedicate this piece of work to you my father; the late Willie Kaiasi and my uncle; the late John Haurae.
Acknowledgment

I am grateful to the following people and institutions for their contributions and support toward successful completion of this research project.

Dr. Jonathan Vigh, for his mentoring sessions on tropical cyclones, meteorological concepts, and NCL programming for data analysis. He is serving as my co-supervisor and is formally part of my supervisory committee. I am grateful for his suggestions and comments toward the climatology analysis. Furthermore, Dr. Vigh is also the founder of exploring funding opportunities for my NCAR trip. He is a project scientist at the Joint Numerical Testbed (JNT) of the Research Application Laboratory (RAL) of the National Center for Atmospheric Research (NCAR).

Dr. James Done, for his ideas and contributions toward my statistical downscaling analysis. He is part of my supervisory team, serving as research advisor, and I’m thankful for his time in reviewing all my draft reports. Dr. Done is a project scientist at the Mesoscale and Microscale Meteorology (MMM) Division of the NCAR Earth System Laboratory (NESL).

Professor Elisabeth Holland, for her advice, comments, and suggestions in the data analysis and interpretation of results. She is the principal supervisor of the supervisory team, and I’m grateful for all her assistance toward the completion of my thesis.

Dr. Cindy Bruyère, for preparing and providing the NCEP/NCAR reanalysis and future simulation datasets. I’m also thankful for her expertise on the underlying principles and processes in statistical downscaling of tropical cyclones. She was instrumental in providing new directions when challenges arose. Dr. Bruyère is a project scientist at the MMM Regional Climate Group, and she also served as a member of my supervisory committee during the NCAR trip.

I also extend my sincere gratitude to Professor Kerry Emmanuel for his time in responding via email to my doubts and questions regarding the development and performance of his tropical cyclone genesis index (Genesis Potential Index). He is a Professor of Atmospheric Science at Massachusetts Institute of Technology (MIT).

Furthermore, I gratefully acknowledge Dr. Greg Holland for his support when I encountered challenges. His contributions toward the analysis of my results are also much appreciated. He
is a senior scientist studying hurricanes, tropical meteorology and severe local storms at MMM.

I highly appreciate all PACE–SD postgraduate students of year 2013–2014. Their suggestions, comments, encouragements, and sharing of resources have positively influenced the successful completion of this thesis project. In particular, I am grateful for Mr. Reginald Reuben for preparing the maps used in this report.

I would also thank PACE–SD (EU–USP Climate Change Scholarship), NESL Diversity funds, MMM (Cindy Bruyère’s Nested Regional Climate Model Group), and RAL Diversity Funds for sponsoring this research project until completion.
Abstract
Statistical downscaling (SD) is a commonly used approach to infer tropical cyclone (TC) activity in global climate model output. It employs TC genesis indices to assess TC activity in current and future climate. Because conclusions in the literature are inconsistent about how TC activity will change under future warming and how they have changed in the past due to climate variability, more work is needed to determine the value of SD for understanding TC genesis in the South Pacific (SP). This study (1) assesses the observed historical TC activity, (2) strives to improve the performance of two existing indices—the Genesis Potential Index (GP) and the Cyclone Genesis Index (CGI)—for the SP using NCEP/NCAR reanalysis data and comparisons with observations, and (3) applies these indices to future climate data to infer future behaviour of TCs in the SP. Observed TC activity varies on a range of timescales. The El Niño Southern Oscillation (ENSO) cycle has considerable influence on the spatial distribution of observed TC activity on interannual timescales in the region. Peak TC activity occurs during the El Niño years in the eastern part of the basin and shifts to the western region during La Niña years. Furthermore, the western part of the basin receives the majority of TC events, with Category 1–4 TCs being most common; the eastern side of the basin experiences less activity. Observed TCs also vary on decadal timescales, and the annual frequency of TCs has decreased in the recent decade. While Category 1–3 TCs decreased in the recent two decades (1991–2010) a slight increase was recorded for Category 4 and 5 TCs during 1981–2010.

A useful index should be able to capture observed interannual variations in the recent climate. However, both GP and CGI usefully captured the observed annual frequency of TCs recorded in the entire South Pacific Ocean (0–40S, 135E–120W), but only when GP and CGI are applied over a hotspot region (10N–30S, 150W–70W) of genesis development in the SPO. When the indices are applied to the period 1981–2010, the GP explains about 17% of observed variations, while the CGI explained 19%; this skill is modest at best. When applied to a future climate scenario using Community Climate System Model output under the A2 emission scenario, GP predicts a 41% decrease and CGI predicts a 10% decrease in the favorable environment for TC activity by the end of 21st century on interannual timescale. Future research is needed to develop a specific genesis index for the SP basin and to understand the physical mechanisms to improve TC assessments in the region.
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<th>Description</th>
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<tbody>
<tr>
<td>AOGCM(s)</td>
<td>Atmosphere–Ocean Global Climate Model(s)</td>
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<tr>
<td>AGCM(s)</td>
<td>Atmosphere Global Climate Model(s)</td>
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<tr>
<td>APRC</td>
<td>Asia Pacific Research Centre</td>
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<td>CDD</td>
<td>CSIRO Direct Detection Scheme</td>
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<td>CGI</td>
<td>Cyclone Genesis Index</td>
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<tr>
<td>CMIP3</td>
<td>Coupled Model Intercomparison Project Phase 3</td>
</tr>
<tr>
<td>CVP</td>
<td>Curvature Vorticity Parameter</td>
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<tr>
<td>CVPS</td>
<td>Curvature Vorticity Parameter Scheme</td>
</tr>
<tr>
<td>DARLAM</td>
<td>Division of Atmospheric Research Limited Area Model</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Center for Medium-Range Weather Forecast</td>
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<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
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<td>EOF(s)</td>
<td>Empirical Orthogonal Function(s)</td>
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<td>ER</td>
<td>Equatorial Rossby waves</td>
</tr>
<tr>
<td>FSM</td>
<td>Federated States of Micronesia</td>
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<td>GCM(s)</td>
<td>Global Climate Model(s)</td>
</tr>
<tr>
<td>GISS–AOM</td>
<td>Goddard Institute for Space Studies Atmosphere-Ocean Model</td>
</tr>
<tr>
<td>GISS–ER</td>
<td>Goddard Institute for Space Studies ModelE</td>
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<tr>
<td>GPI</td>
<td>Genesis Potential Index</td>
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<tr>
<td>IBTrACs</td>
<td>International Best Track Archives for Climate Stewardship</td>
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<tr>
<td>INM-CM3.0</td>
<td>Institute of Numerical Mathematics Coupled Model Version 3.0</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>ITCZ</td>
<td>Intertropical Convergence Zone</td>
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<td>JTWC</td>
<td>Joint Typhoon Warming Centre</td>
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<td>LMCP</td>
<td>Lifetime minimum central pressure</td>
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<td>MDR</td>
<td>Main Development Region</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<td>MJO</td>
<td>Madden–Julian Oscillation</td>
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<td>MRG</td>
<td>Mixed Rossby–gravity waves</td>
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<tr>
<td>MYCGP</td>
<td>Modified Yearly Convective Genesis Potential Index</td>
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<tr>
<td>NCAR</td>
<td>National Center for Atmospheric Research</td>
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<td>NCEP</td>
<td>National Centers for Environmental Prediction</td>
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<td>NCL</td>
<td>NCAR Command Language</td>
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<td>NH</td>
<td>Northern Hemisphere</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>OLR</td>
<td>Outgoing longwave radiation</td>
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<td>ONI</td>
<td>Oceanic Niño Index</td>
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<tr>
<td>PACE-SD</td>
<td>Pacific Center for Environment and Sustainable Development</td>
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<tr>
<td>PCCSP</td>
<td>Pacific Climate Change Science Program</td>
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<tr>
<td>PI</td>
<td>Potential Intensity</td>
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<td>PICs</td>
<td>Pacific Island Countries</td>
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<td>PNG</td>
<td>Papua New Guinea</td>
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<tr>
<td>RCM</td>
<td>Regional Climate Model</td>
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<td>RSMC</td>
<td>Regional Specialized Meteorological Centre</td>
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<tr>
<td>SD</td>
<td>Statistical downscaling</td>
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<tr>
<td>SGF</td>
<td>Seasonal Genesis Frequency</td>
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<td>SH</td>
<td>Southern Hemisphere</td>
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<tr>
<td>SHTC</td>
<td>Southern Hemisphere Tropical Cyclone</td>
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<tr>
<td>SIO</td>
<td>South Indian Ocean</td>
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<tr>
<td>SOI</td>
<td>Southern Oscillation index</td>
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<td>SPEArTC</td>
<td>Southwest Pacific Enhanced Archive for Tropical Cyclones</td>
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<tr>
<td>SPO</td>
<td>South Pacific Ocean</td>
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<th>Definition</th>
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<tr>
<td>SST</td>
<td>Sea Surface Temperature</td>
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<tr>
<td>SWP</td>
<td>Southwest Pacific</td>
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<tr>
<td>TC(s)</td>
<td>Tropical cyclone(s)</td>
</tr>
<tr>
<td>USP</td>
<td>University of the South Pacific</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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<tr>
<td>WPM</td>
<td>West Pacific Monsoon</td>
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CHAPTER 1 INTRODUCTION

1.1 Overview of TCs in the South Pacific basin

Because of their potentially devastating human and physical impacts, the question of how tropical cyclone (TC) activity over the South Pacific (SP) has evolved and may change in a warming climate requires further investigations. During the period 1950–2004, 3.4 million people were affected by natural disasters in the SP and over 1,700 fatalities were recorded in that region—except for Papua New Guinea (PNG) (World Bank, 2006). TC activity accounts for about 75% of the reported natural disasters (World Bank, 2006). Undoubtedly, TC activity and its related impacts have been threatened the livelihood and economy of Pacific Island Countries (PICs) (Australian Bureau of Meteorology & CSIRO, 2011a; Hamnett, 1995; World Bank, 2006). To develop appropriate adaptation measures and strategies at regional, national, and societal levels, researchers must initially understand the underlying mechanisms that control TC behaviour in the SP basin (Australian Bureau of Meteorology & CSIRO, 2011a). Indeed society’s real need and perhaps one of the great challenges for the scientific community (Emanuel & Nolan, 2004) is to understand the behaviour of TC activity in the region and to comprehensively infer what the future may hold in response to increasing greenhouse gas concentrations in the Earth’s atmosphere (Meehl et al., 2007; Walsh, 2004).

However, even the highest-resolution climate models do not have sufficient fidelity to realistically simulate the observed frequency of TCs of different intensities at global and regional scales, let alone the inner core of a TC system, making future TC activity a significant research problem for many TC basins including the South Pacific Ocean (SPO) (Camargo, 2013; Knutson et al., 2008; Walsh, 2004). In recent decades, it has been well reported that researchers have come to different conclusions with uncertainties about projected TC behaviour at both the regional and global scales in future climate scenarios (Knutson et al., 2010; Webster et al., 2005). In the SP basin, a decrease in TC frequency was projected while strength of severe TC system is likely to increase by the 21st century under a warming environment (Australian Bureau of Meteorology & CSIRO, 2011a; Nguyen & Walsh, 2001). With the uncertainties in climate models, different techniques of inferring future TC behaviour are useful so that new results can be assessed against existing conclusions. The subject of how global climate change and variability (whether natural or anthropogenic) will alter future TC activity in the SP is therefore completely unresolved for
decision makers, and because it only attracts very few studies at regional and local scale in the literature (Australian Bureau of Meteorology & CSIRO, 2011b; Nguyen & Walsh, 2001), future TC behaviour remains a subject of investigation and debate in the scientific community.

1.2 How statistical downscaling is applied to TC activity

Statistical downscaling (SD) aims to improve fidelity of TC activity in Global Climate Model (GCM) runs at a smaller scale or for a specific region. It is a technique for acquiring high-resolution climate information from coarse–resolution GCM outputs (Benestad et al., 2007). Because GCMs struggle to realistically capture or even fail to resolve TC activity, atmospheric scientists use tropical cyclone indices to determine TC activity from GCM output (Australian Bureau of Meteorology & CSIRO, 2011b; Camargo, 2013; S J. Camargo et al., 2007; Emanuel, 2010). The use of empirical relationships between large–scale climate data and TC activity such as the Genesis Potential Index (known as GP in this study) (Emanuel & Nolan, 2004) and Cyclone Genesis Index (CGI) (Bruyère et al., 2012) to acquire climate information on TC activity for a given region is called statistical downscaling of TC activity. It is possible because TC indices are composed of the large–scale environmental factors (predictors) that are known to control TC formation, namely potential intensity, wind shear, relative humidity, and absolute vorticity (Bruyère et al., 2012; Emanuel & Nolan, 2004; Gray, 1968). Since GCMs are capable of simulating large–scale environmental factors rather than TCs themselves, this approach is a way to determine TC activity in GCM–simulated data. By identifying TC genesis indices vorticity in GCM–simulated data, relevant information on TC activity can be acquired at the regional scale.

1.3 Background information for this study

This study uses an SD approach to understand the present and the potential behaviour of future TC activity over the SP by application of TC genesis indices. The Pacific Climate Change Science Program (PCCSP) report concluded that future TC activity will decrease in the SP after applying GP (Emanuel & Nolan, 2004) to selected Coupled Model Intercomparison Project 3 (CMIP3) outputs (Australian Bureau of Meteorology & CSIRO, 2011a). Similarly, a regional decrease in TC activity is expected after a statistical downscaling approach is applied to selected Coupled Model Intercomparison Project 5 (CMIP5) outputs over the SP by the end of 21st century (Camargo, 2013; Emanuel, 2013).
Apart from the SD approach, direct simulation shows a regional future decrease of TC activity by the end of the 21st century under a warming environment (Nguyen & Walsh, 2001). Though SD and direct simulations agree with similar results, none of these studies have examined the level of confidence provided by different TC genesis indices in capturing past and current TC activity for the SP basin, thereby questioning the uncertainty in TC predictions for the SP basin. In advancing this line of inquiry, this study first verifies the skill of two existing TC genesis indices with observed variations in TC activity in the SP basin, then it proceeds to downscale future climate over the entire SP basin using a GCM–simulated climate dataset.

1.4 Problem statement

The purpose of this study is to first examine and improve the performance of two existing TC genesis indices by application to a reanalysis model dataset and comparison with observed TC activity in the SP basin. Second, the verified indices will be applied to GCM output to infer possible TC behaviour through the 21st century. Specifically, this study addresses the following questions:

1. Which of the two existing TC genesis indices displays highest correlation with observed TC activity in the SP?

2. How well does the NCEP/NCAR Reanalysis represent observed TC activity in the SP basin?

3. How can the performance of the existing TC genesis indices be improved for current climate over the SP basin?

4. Will a warming global climate provide a more, or less, favorable environment for TC activity?

1.5 Study objectives

In answering the preceding questions, this study has four key objectives:

1. To assess the level of observed TC activity in the South Pacific basin over the period 1981–2010.
2. To illustrate the current skill of two existing TC genesis indices in the SP basin, then further investigate methods of improvement if required.

3. To compare historical observations of TC activity in the South Pacific basin with large-scale environmental factors known to influence tropical cyclogenesis in the NCEP/NCAR reanalysis model.

4. To predict future TC from CMIP3–Community Climate System Model (CCSM) output using the statistical downscaling approach.

1.6 Implications of this study

PICs and territories can potentially benefit from this study in the following ways. First, people, homes, and essential resources in the region are vulnerable to TC activity and its related impacts every year, yet this region is one of the most underserved cyclone basins in the world both in facilities and human capacity. This is evident through national and regional reliance on models and expertise of the First World, hence this study sets a new era of significant research problems for regional students at the University of the South Pacific (USP). Furthermore, this study conveys climate information about future behaviour of TC activity in the region so that environmental adaptation practitioners and decision makers can effectively plan for the future in enhancing existing disaster risk management strategies and practices and relevant impacts studies in the region. Finally, this study serves as baseline information for related future studies on TC assessment in the South Pacific. This is a regional contribution to the scientific community in researching and explaining current and future behaviour of TC activity in the region.

1.7 Structure of this report

This report is organized into six chapters. Chapter 2 presents a literature review to establish a foundation for the key study problem. Chapter 3 presents detailed descriptions of datasets, tools, and analysis procedures. Chapter 4 presents the results obtained from data analysis. Chapter 5 further interprets both the methods and results. The conclusions and recommendations follow in Chapter 6. Appendix A presents additional useful figures and meanings of important terminology.
CHAPTER 2 REVIEW OF PRECEDING STUDIES

2.1 Introducing the SP basin

The South Pacific basin is one of the planet’s hotspots of tropical cyclone (TC) activity. Every year, approximately 80 TCs develop across the world’s tropical belt, and about 27 of these occur in the southern hemisphere (Gray, 1975). The SP region alone receives about nine TC events on average per year (Ramsay, 2011). While this ratio to total activity is lower than other TC basins (e.g., North Atlantic and Northwest Pacific basins), it is nevertheless significant to highly vulnerable PICs. TCs severely affect navigators, farmers, the tourism and fishing industries, the lives of coastal dwellers, and national economies (Kuleshov, 2012). Examples of high-impact TCs in recent years include TC Zoe at the Solomon Islands (maximum intensity of 240 km/h) in December 2004, TC Heta at American Samoa (maximum intensity of 235 km/h) in January 2004 (Kuleshov, 2012), TC Evans at Fiji and Samoa (maximum intensity of 270 km/h) in December 2012, and TC Lusi at Vanuatu (maximum intensity of 93 km/h) in March 2014 (Fiji Meteorological Service, 2014), and TC Pam (maximum intensity of 250 km/hr) at Solomon Islands and Vanuatu in March 2015 (International Federation of Red Cross & Red Crescent Societies, 2015). The SP experiences significant TC activity that threatens the livelihood of Pacific Islanders.

PICs rely on the Regional Specialized Meteorological Centre (RSMC) in Nadi for TC forecasting. The term *tropical cyclone* is commonly used for a non-frontal synoptic-scale low-pressure system that forms over tropical waters with organized convection (thunderstorm activity) and a specific surface wind circulation (Holland, 1993). In this study, tropical cyclones are used for systems with a maximum sustained wind speed of 34 knots (about 63 km/hr) and above. The terms *severe* and *intense* TC are used to refer to categories 3–5 TCs following the Australian TC intensity scale standard (Fiji Meteorological Service, 2014). According to the World Meteorological Organization (WMO), this territory at 0–30°S, 160°E–120°W (definition of SP basin in this study) is the domain of the Fiji Meteorological Service (FMS) in Nadi, Fiji, while RSMC in Wellington provides meteorological services to the domain 30°S–40°S, 160°E–120°W. These two regions together are called the South Pacific Ocean (SPO) in this study. The RSMCs play important roles in monitoring and providing TC advisories to the island countries through the national meteorological agents in the region so that TC warnings are received at least 24 hours in advance (WMO, 2011).
The climatology of TCs in the SP and the data approach for this study are presented in this chapter. It begins with the influence of climate variability and large environmental features on cyclogenesis, then proceeds to explain the development of TC genesis indices and different approaches to how TC activity is determined from GCM simulations. The focus here is to provide a snapshot of climatology and the underlying principles of a statistical downscaling approach to TC activity, as well as to demonstrate how prior studies and methods vary and thereby motivate the need for this study.

2.2 Best track datasets for SP

Multiple records of best track datasets are available for the SP basin. The term best track refers to the historical record of observed TC activity showing but not limited to the locations and the intensity of a TC through its lifetime (NOAA, 2013). Preceding studies employed different best track datasets in the SPO, depending on each study’s purpose and the researchers’ familiarity with the dataset format. Datasets include the Southern Hemisphere Tropical Cyclone (SHTC) archive from the National Climate Centre of the Australian Bureau of Meteorology (Kuleshov et al., 2012), the Southwest Pacific Enhanced Archive for Tropical Cyclones (SPEArTC) from the Asia Pacific Research Centre (APRC) (Diamond et al., 2012), the International Best Track Archives for Climate Stewardship (IBTrACs) from WMO, and the historical record from the Meteorological Service of New Zealand Limited. These archives consist of historical records from RSMCs in Nadi and Wellington jointly with their own sources of observations (Diamond et al., 2012; Kuleshov 2012). Apart from these archives, the Joint Typhoon Warning Centre (JTWC)–a non-RSMC that has been serving the SPO in TC forecasting–also has its own best track record for interested parties. One main difference is that observations in the JTWC best track use one-minute average wind speed, while the rest use 10–minute average wind speed. Neither approach is incorrect, but a 10–minute average wind speed follows the WMO standard (Otto-Bliesner, 2009).

2.3 Influence of climate variability and large-scale environmental conditions

2.3.1 ENSO phases and observed TC activity

The ENSO cycle has significant influence on the spatial distribution of TC activity across the central equatorial Pacific (Figure 1). Based on historical records, TC activity in the western part of the region and near the northeast coast of Australia (110°E–155°E) is usually higher
during La Niña (cold phase) years than during the neutral and El Niño periods (warm phase) (Australian Bureau of Meteorology & CSIRO, 2011b; Hastings, 1990; Kuleshov et al., 2012). In contrast, TC events during El Niño years are more frequent in the eastern Pacific, the central Pacific, and further east of the international dateline to longitude 120°W (Basher & Zheng, 1995; Diamond et al., 2013; Kuleshov et al., 2012). This effect is so strong that French Polynesia, which rarely experiences TCs, does record TC events during El Niño events (Camargo et al., 2006). During neutral years, the spatial distribution of TCs tends to be concentrated in the western-central part of the equatorial Pacific, and the frequency is not any higher here than during the cold and warm phase years (Kuleshov et al., 2009). Thus, the ENSO cycle plays a key role in the modulation and distribution of TC activity across the equatorial Pacific.

The influence of the ENSO cycle is also evident at sub–regional scales with north-south movement of TC events. In a recent study, TC genesis is active in the region from north of Fiji through Samoa, and is more intense around latitude 10°S and longitude 180 degrees (Chand & Walsh, 2009). Apart from an east–west shift, there is also a meridional displacement. During the warm phase periods, the mean genesis location shifts northward; during cold phase years, it shifts southward (Suzana J Camargo et al., 2007). This illustrates that the ENSO cycle has a significant relationship with the occurrence of TC in sub–regions.

Figure 1. Locations where TCs formed over the entire South Pacific Ocean during 1969–2006 during neutral years, El Niño years, and La Niña years. Genesis locations are defined here as the points where TC central pressure is estimated to have dropped to 1000 or below (Kuleshov et al., 2009).
However, while only the frequency of tropical cyclones has been considered in prior studies (Chand et al., 2013; Camargo et al., 2006; Diamond et al., 2013; Kuleshov et al., 2009) ENSO can also influence other TC metrics such as intensity and duration of TC. While shifts in location and frequency of TCs have significant correlation with the phases of ENSO in both sub-regions and the entire equatorial Pacific, other important TC metrics are not sufficiently covered for recent climate in the SP.

2.3.2 Position of large-scale environmental variables

The spatial distribution of TC activity is correlated with the position of large-scale environmental factors. First, the seasonal cycle and movement of SST are well documented and correlated with the distribution of TCs across the equatorial Pacific (e.g., Basher and Zheng 1995, Chand and Wash 2009; Kuleshov et al., 2012). For instance, during the TC season, positive average SST anomalies tend to occur near the equator with the highest record further east at 0–15°S, 160°E–140°W. In contrast, negative anomalies tend to occur westward in the Coral Sea of Australia. In the cold phases, positive anomalies shift westward while negative anomalies are dominant in the equatorial region and further east between 15°S and the equator (Figure 2) (Chand & Walsh, 2009; Kuleshov et al., 2012). According to Kuleshov (2012), the position of positive anomalies of SST is associated with TC activity during El Niño in the western Pacific and during La Niña in the eastern side. Similarly, the position of weak wind shear across the equatorial Pacific has great correlation with the ENSO phases. Vertical wind shear is defined as the vector difference between wind speeds at a given levels, typically 850–200 hPa (DeMaria, 1996; Emanuel & Nolan, 2004; Kuleshov et al., 2012). Historical records show that vertical wind shear is moderately weak (<8ms⁻¹) during warm phase seasons over the central region and further in the eastern region at latitudes 13°S–14°S than in the western Pacific (Figure 3). In contrast, weak wind shear tends to move westward during the cool phase with the lowest values centered near 160°E–175°E, 15°S–20°S (Kuleshov, 2012). Weak wind shear associated with ENSO and high TC activity are therefore co-located. Indeed, Gray (1979) and DeMaria (1996) showed that low vertical shear is a favorable condition while strong vertical shear restrains genesis activity.

Finally, vorticity is a contributing factor to TC formation during ENSO cycle phases. It refers to the quantity of local rotation or spin in the atmosphere at a specified level. For instance, observations show that negative (cyclonic) vorticity anomalies between latitudes 5°S–15°S
help to explain the enhanced tropical cyclogenesis that occurs in the near–equatorial regions and the higher TC activity that occurs in the eastern part of the basin during the El Niño.

Figure 2. SST anomalies (°C) from November to April in SPO during (a) warm phases and (b) La Niña episodes. Shaded regions indicate statistical significance at 95% interval (Kuleshov, 2012).
At the same time, a region of positive (anti–cyclonic) anomalies found around the equator helps to suppress TC events closer to the equator. During the cold phase episodes, negative anomalies of vorticity are observed in the western part of the basin resulting in enhanced TC activity around Australia (Kuleshov, 2012; Gray, 1975).

In summary, these large–scale environmental factors play crucial roles for TC formation in the SP basin. Historical observations show that SST, wind shear, relative humidity, and vorticity are required conditions and explain the spatial distribution of genesis activity across the basin with respect to the warm and cold phases of the ENSO cycle (Gray, 1979; Kuleshov, 2012). Section 2.5 of this chapter discusses the development of empirical relationships based on these factors.

Figure 3. Vertical wind shear ($U_{200}-U_{850}$) (m/s) in SPO over the region of the SPO during (a) warm and (b) cold phases. Shaded fractions indicate statistical significance at 95% interval (Kuleshov, 2012).
2.3.3 Equatorial waves and cyclogenesis

Equatorial waves play an important role in initiating TC formation. There are five well-known forms of equatorial waves with a period of two days or longer (Frank & Roundy, 2006). These include the Madden–Julian Oscillation (MJO), equatorial Rossby waves (ER), mixed Rossby–gravity waves (MRG), Kelvin waves, and tropical–depression–type waves (TD). This review found that very few studies have investigated the role of equatorial waves for tropical cyclogenesis over the South Pacific until the recent decade.

The significance of equatorial waves in tropical cyclogenesis has recently been investigated by analyzing global tropical circulation. A 20–year period of observed outgoing longwave radiation (OLR) was analyzed to show a significant correlation between the equatorial waves and TC development, especially with Kelvin waves, for the six defined active TC basins. The SP basin shows no propensity to tropical cyclogenesis when it has active MJO or ER activity. However, there is a weak tendency for cyclogenesis when MRG–TD–type activity is above normal. A possible reason could be that higher–frequency waves are not often as strong in the SH as they are in the NH (Frank & Roundy, 2006). Furthermore, Chand and Wash (2010) agreed with Frank and Roundy (2006) after investigating the influence of MJO on TC activity in the region of Fiji, Samoa, and Tonga (central–east Pacific). Based on the JTWC best track data, the enhanced phase of MJO has a tendency to modulate TC genesis with a best estimate of 5 times more cyclone formation than during inactive periods of MJO. Moreover, this modulation is further enhanced when it falls in El Niño periods (Chand & Walsh, 2010). This indicates that the impact of MJO is modified by the ENSO cycle. Further research is required to improve understanding of the physical mechanism and correlations between TC genesis and tropical waves.

2.3.4 Role of SPCZ in tropical cyclogenesis

The position of the South Pacific Convergence Zone (SPCZ) plays an important role in TC formation and the Southern Hemisphere’s climate. The SPCZ (Figure 4) is the most persistent large–scale rain band in the Southern Hemisphere, extending northwest to southeast from the western Pacific warm pool and southeast toward French Polynesia (Kiladis et al., 1989). Preceding studies have shown that a shift in the mean position of the SPCZ explains some of the TC genesis changes east and west of the international dateline (Kiladis et al., 1989; Vincent et al., 2011). According to Vincent et al., (2011), the orientation and position of
SPCZ falls into four categories during the austral summer (Figure 5): the neutral phase refers to years when SPCZ is close to the climatological position. The negative phase refers to years when SPCZ is displaced by 3 degrees south, while the positive phase represents SPCZ displaced by 3 degrees north of its climatological position. These are described as diagonal orientation of SPCZ. In contrast, the asymmetric phase refers to the zonal orientation of SPCZ at 6 degrees south. SPCZ locations can constrain cyclogenesis to occur at 10 degrees south of the SPCZ because the arrangement of atmosphere in the SPCZ region supports all large–scale atmospheric variables necessary for TCs (Vincent et al., 2011). Additionally, cyclogenesis in the central–eastern Pacific as far as French Polynesia is related to the zonal orientation of the SPCZ, a conclusion that is independent of the general effect of El Niño events (Vincent et al., 2011). This indicates that there is a strong relationship between El Niño and SPCZ in relation to TC activity in the SP basin. Even though the significance of SPCZ to the Pacific’s weather patterns is well known, its characteristics, dynamics, and variability have received little attention in the literature.

Figure 4. SPCZ’s normal position as it stretches from the warm pool waters to the Solomon Islands, through Fiji, Samoa, and Tonga (Australian Bureau of Meteorology & CSIRO, 2011b).
Figure 5. (a) The four major orientations of the SPCZ. The asymmetric location with the east-west orientation is shown in red. (b) Precipitation flux associated with the different positions (Vincent et al., 2011).

2.4 Observed TC activity in recent climate

Assessment of the historical record indicates there is no clear trend in the observed number of TCs in recent decades over the SPO. In a study on trend analysis, Kuleshov et. al., (2010) applied a nonparametric Monte Carlo method to assess the level of observed TC activity and concluded that there is no statistically significant trend in the total number of TCs that have reached a lifetime minimum central pressure (LMCP) of 995 hPa or lower over the SPO for the period 1982–2007. Even for severe TCs and the most intense TCs (TCs that reached 970 hPa or lower), a similar conclusion was reached for the SPO when using the TC archive for the Southern Hemisphere (Kuleshov et al., 2010). In contrast, the Southern Hemisphere as a whole has seen an increase (Kuleshov et al., 2010), and the planet has seen an increase in the number of intense TCs (TC categories 4 and 5 on the Saffir–Simpson scale) during the 35–year period prior to year 2004 (Webster et al., 2005). The hemispherical analysis covers observations in the South Indian Ocean (SIO) which has a significant increasing trend, while intense TCs have not increased significantly in the SPO during this period (Kuleshov et al., 2010). However, improved detection of intense TCs by newly implemented observing systems in the recent decade might be a contributing factor to uncertainty in intense–TC trend analysis (Kuleshov et al., 2010). Contrasting results from trend analyses at global and regional scales motivate the need for site–specific studies to better understand trends.
In the PICs and territories, the observed average number of TC events varied over the period 1969–2010. According to the Pacific Climate Change Science Program (PCCSP) report, individual country analysis showed that there has been no significant trend in the average number of TCs passing each country’s capital within a domain of 400 kilometres per season in PNG, Samoa, and the Solomon Islands (Figures 6A, 6B, and 6C) (Australian Bureau of Meteorology & CSIRO, 2011a).

**Figure 6.** Number of TCs recorded within 400 km for selected countries over the period 1969–2010. The purple lines represent the variation in average occurrence of TC in (A) PNG, (B) Samoa, (C) Solomon Islands, and (D) Vanuatu (Australian Bureau of Meteorology & CSIRO, 2011a).

In contrast, the average annual number of observed TCs during the last 7–8 seasons shows a significant decrease in Vanuatu (Figure 6D). This illustrates that the smaller the domain of the study, the more the results vary across the equatorial Pacific. Although conclusions obtained by global and regional studies are theoretically correct, the small sample size reduces the significance of the results for a particular location. Additionally, analyzing meteorological observations in the SPO is problematic because this region suffers from poor
data quality such as missing records and poor homogenous control of historical records over the early decades until the satellite era that began in the early 1990s (Diamond et al., 2012). Moreover, previous TC events have severe direct impact on records and early instruments (Diamond et al., 2012; Landsea et al., 2004). These factors all reduce the accuracy of historical TC observations in the SPO.

2.5 Tropical cyclone genesis indices

2.5.1 Inception and development of genesis indices

The initiation of empirical relationships (TC genesis indices) that explain TC activity began in the 1970s. Though TC formation in the SP is influenced by different climate features such as SPCZ, tropical waves, and climate variability such as extreme ENSO phases, large-scale environmental variables have been shown to control the development of TCs in tropical circulation (Gray, 1968; Gray, 1975) in the atmosphere–ocean setting that is responsible for tropical cyclogenesis. In this study, the term “large-scale factors” is used interchangeably with “predictors” (Benestad et al., 2007).

To explain the seasonal frequency of TC activity, Gray (1975) initially assembled the following predictors into a numerical equation known as the Seasonal Genesis Frequency (SGF): SST of at least 26.5°C at a depth of ~60 meters, mid-level moisture, conditionally unstable atmosphere, low-level vorticity, and vertical wind shear through a deep atmospheric layer. In 1998, the SGF index was further improved to become the Modified Yearly Convective Genesis Potential Index (MYCGP) by addressing the enhanced oceanic energy associated in the previous index (Royer et al., 1998). Emanuel and Nolan (2004) refined Gray’s index by addressing the use of threshold temperature, which is believed to be less important in future climate change studies; instead they established the Genesis Potential Index (GP). Recently, improvements have been made with the development of indices at regional scales—for instance (Bruyère et al., 2012; Tippett et al., 2011). The evolution of Gray’s effort follows the ability to reproduce observed (1) global frequency of TC activity (Gray, 1975), (2) frequency of TC activity on a seasonal hemispherical basis (Emanuel & Nolan, 2004), and (3) interannual variations of TC activity at regional scale (Bruyère et al., 2012). However, these indices are based on the theory that SST, relative humidity, vorticity, and vertical wind shear are contributing factors to TC formation. The following paragraph
presents the method, datasets, and other details in the development of the empirical relationships.

2.5.2 Datasets used to develop genesis indices

Reanalysis datasets are useful resources for assessing TC activity in the recent and present climate. Gray (1979) used observed, large-scale environmental variables during 20 years of global observations (1952–1971) to test the ability of the SGF to reproduce recent climate. However, early observations suffer from poor data quality issues (Landsea et al., 2004) and therefore lead researchers to choose reanalysis datasets for their studies (Bruyère et al., 2012; Emanuel and Nolan 2004). For instance, the NCEP/NCAR and ECMWF reanalysis datasets were successfully used in the North Atlantic basin instead of observational data (Bruyère et al., 2012). Bruyère et al., (2012) showed that observed TCs in the North Atlantic were correlated with CGI predictions having values of $R^2 = 0.87$ when applied in the NCEP/NCAR dataset, and $R^2 = 0.95$ for the ECMWF dataset. This insignificant difference of 0.08 places both reanalysis datasets at the 99% confidence level, indicating that related future studies can employ either of these two reanalysis datasets.

2.5.3 Manipulation of predictors

The development of GP by Emanuel and Nolan (2004) illustrates an empirical relationship that explains TC activity reasonably well. Based on SGF by Gray (1979), GP emerged by eliminating predictors such as threshold SST which does not account for the variations of temperature under climate change and instead uses potential intensity because it depends entirely on air–sea imbalance (Emanuel & Nolan, 2004). GP is then numerically represented as:

$$GP = \left(10^5 \eta \right)^{3/2} \left[ \frac{RH}{50} \right]^3 \left[ \frac{PI}{70} \right]^3 \left(1 + 0.1V_{\text{shear}}\right)^2$$

where GP is the genesis potential index, $\eta$ is absolute vorticity ($s^{-1}$) at 850 hPa, RH is the relative humidity (%) at 700 hPa, PI is potential intensity ($ms^{-1}$), and $V_{\text{shear}}$ is the vertical wind shear ($ms^{-1}$) between 850 and 200 hPa (Emanuel & Nolan, 2004). CGI is a similar index:
By eliminating vorticity and relative humidity from GP, CGI became a better index for the North Atlantic basin (Bruyère et al., 2012). The goal of manipulating predictors is to determine which predictors are functionally applicable together to reproduce past TC climatology at global and regional levels on different timescales. Better performance with fewer predictors (e.g., Bruyère et al., 2012) reflects the concept of “necessary but not sufficient conditions” for TC formation as stated by Gray (1975).

\[ CGI = \left( \frac{PI}{70} \right)^3 \left( 1 + 0.1V_{\text{shear}} \right)^{-2} \]

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**Figure 7.** The number of genesis events in the 30-year period in the northern hemisphere (left) and the southern hemisphere (right). The blue lines indicate the number of observed TCs, and the green lines show the predicted TCs (Emanuel & Nolan, 2004).

### 2.5.4 Testing TC genesis index

From the few studies conducted thus far, genesis indices have been tested at seasonal and interannual timescales and were applied at global, hemispheric, and regional (basin) scales. Confidence in TC genesis indices depends on their skill in predicting observations in recent climate. Researchers were only interested in the frequency of TCs in this approach, while important metrics such as intensity, distribution, and duration were not considered. For instance, GP has the skill to capture seasonal frequency of TC activity in both hemispheres during a 30–year period (Figure 7) (Emanuel & Nolan, 2004). However, GP fails to predict observed variations at interannual timescales (Bruyère et al., 2012). Moreover, when using the NCEP/NCAR and ECMWF reanalysis datasets, CGI shows more skill in reproducing both the seasonal and interannual frequency of observed TC activity in the North Atlantic basin, but only when CGI is applied over the main development region of TC formation.
A better index would have the ability to predict observations at both seasonal and interannual timescales, and CGI is found to be a better index for the North Atlantic basin (Bruyère et al., 2012).

![Graph showing the five-year running mean of observed TC frequency in the North Atlantic compared to estimated frequencies obtained by applying CGI to two reanalysis datasets, NCEP/NCAR (red) and ECMWF (blue).](Image)

**Figure 8.** The five-year running mean of observed TC frequency in the North Atlantic is indicated by the black line, and the other colors show estimated TC frequencies obtained by applying CGI to two reanalysis datasets, NCEP/NCAR (red) and ECMWF (blue) (Bruyère et al., 2012).

### 2.6 Introducing GCMs and simulation of TC activity

Simulating TC activity is a challenging task in climate modeling because such complex weather systems are difficult to resolve in current–generation GCMs. GCMs are numerical representations of the climate developed from the functions of Atmosphere General Circulation Models (AGCMs), and they are important tools for daily weather prediction. Based on the laws of physics, model developers use mathematical equations based on the laws of physics to represent the physical processes that govern interactions between the Earth’s land, atmosphere, ocean, and cryosphere. Climate models simulate the behaviour of climate variables such as wind pressure, surface temperature, rainfall, and humidity, estimate the frequency of climate variables such as El Niño events, and make climate projections for the next 50–100 years (Australian Bureau of Meteorology & CSIRO, 2011b). Multiple experiments show the usefulness of GCMs in simulating Earth’s climate to project the future TC activity at global and regional scales (Benestad et al., 2007; Gualdi et al., 2008; Lavender & Walsh, 2011; Oouchi et al., 2006).
However, features of tropical storms and other related climate phenomena (e.g., tropical waves) exist on smaller spatial scales than can be represented by today’s climate models (Randall et al., 2007). To illustrate, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report presents the skill demonstrated by selected models of the CMIP3 (Meehl et al., 2007) in simulating the frequency and geographical distribution of TCs in recent climate, but failing to resolve TC intensity. This is primarily because GCMs have coarse resolution. Because the ability of the present generation of climate models lacks the skill to simulate the intensity and maximum wind speeds of TC in recent climate, these models have even less skill in realistically inferring future global climate and cannot reliably estimate regional and local–scale events.

2.7 The concept of downscaling

The technique of downscaling emerged because the climate information required for most impact studies is on a finer scale than current GCM simulations can provide (Australian Bureau of Meteorology & CSIRO, 2011b; Benestad et al., 2007; Enke & Spekat, 1997). Downscaling refers to methods that enable scientists to acquire climate information at regional scales by using coarse–resolution climate model outputs (Benestad et al., 2007). There are two approaches: dynamical and statistical downscaling. This section initially discusses these two techniques and provides examples of how they are applied both in the South Pacific and other parts of the planet.

2.7.1 Dynamical downscaling

Dynamical downscaling (also called “numerical downscaling” or “nested modeling”) uses a finer–resolution atmosphere model, a technique pioneered by Giorgi (1990) and then used for simulating TC activity in several studies (Knutson et al., 1998; Lavender & Walsh, 2011; Nguyen & Walsh, 2001; Zhao et al., 2009). Broad–scale climate data from GCMs is used as input to a finer–resolution model—an approach that is technically similar to modeling techniques applied by GCMs—except that the focus is at smaller scales (10–100 km (Australian Bureau of Meteorology & CSIRO, 2011b; Benestad et al., 2007). To illustrate, the CSIRO Mark2 (global model) output is embedded in the CSIRO–DARLAM (regional model) to resolve finer TC climatology, including frequency, intensity, and distribution of TCs over the region 55°S–10°N, 70°E–120°W in an enhanced–CO₂ environment (Nguyen & Walsh, 2001). Though dynamical models have been applied effectively in different regions
across the globe, it is very computationally expensive (Australian Bureau of Meteorology & CSIRO, 2011a; Benestad et al., 2007; Enke & Spekat, 1997). Nevertheless, this approach has been used with success by different research institutions and is recommended by many studies (Knutson et al., 2010; Knutson & Tuleya, 2004; Lavender & Walsh, 2011).

2.7.2 Statistical downscaling

In contrast, statistical downscaling involves the use of empirical relationships to determine climate information over a smaller scale or specific region by using GCM simulation data (Benestad et al., 2007). Though the approach is cheaper and works well in different regions of the globe (Australian Bureau of Meteorology & CSIRO, 2011b; Camargo, 2013; S J. Camargo et al., 2007; Emanuel, 2013; Emanuel et al., 2008), its limitations include the need for several decades of high–quality meteorological data for calibration and verification purposes. Such records are not available for a majority of remote Pacific Islands (Australian Bureau of Meteorology & CSIRO, 2011a). Theoretically, the approach assumes that there is a constant relationship between local weather and large–scale circulation patterns, indicating that observations of the recent/current climate will be the same under any unexpected climate feedbacks and forcing that may occur in the future (Australian Bureau of Meteorology & CSIRO, 2011b). However, this approach is computationally inexpensive and therefore recommended by the IPCC Fourth Assessment Report for Small Island State climate projections (Lupo & Kininmonth, 2008). Furthermore, empirical relationships can be further optimized for predicting desired parameters or variables in present and future climate (Benestad et al., 2007; Camargo, 2013; Emanuel, 2013). Section 2.4 provides detailed information on how researchers develop empirical relationships.

TC genesis indices have been developed in recent decades to acquire TC information from climate model output. For instance, the PCCSP report applied GP to selected CMIP3 model outputs to obtain future behaviour of TCs in the SP basin (Australian Bureau of Meteorology & CSIRO, 2011a). Similarly GP was applied to selected CMIP5 outputs to obtain future climatology of TCs at global (Emanuel, 2013) and regional (Camargo, 2013) scales. Camargo (2013) further argued that because climate models resolve the TC system poorly, climate information on future TCs can be acquired by statistically downscaling individual predictors. This approach has the same goal as direct simulations (see below), except that genesis indices have a theoretical basis and are only applicable to the frequency of TC events (Gray, 1975).
Because these diverse approaches have different strengths and weaknesses, they are all essential for studying future tropical cyclones.

### 2.7.3 Direct simulations

Direct simulation as referred to by Emanuel (2013) is another method for studying TCs in simulated climate data. Though climate models struggle to sufficiently resolve TC features, the current generation of models can perform useful direct simulations. This approach involves using a TC–detection algorithm to identify TC structures directly from global model output. One example is a tracking method that is based on observed TC characteristics as described by Camargo and Zebiak (2002) and Walsh and Watterson (1997). These were used to detect TC–like vortices (TCLVs) and their climatology in the CSIRO Division of Atmospheric Research Limited Area Model (DARLAM) output over the SP region (Nguyen & Walsh, 2001). Similarly, the PCCSP report employed the Curvature Vorticity Parameter Scheme (CVPS) to infer future TC metrics in selected CMIP3 outputs over the SP region (Australian Bureau of Meteorology & CSIRO, 2011a). Though this method only requires a tracking algorithm (Emanuel, 2013), it does not resolve variations in cyclone intensity over time, and it underestimates the observed global frequency of TCs. This is evident at 50–km grid spacing (Zhao et al., 2009), and it estimated fewer than the observed number of TCs in the relevant basins (Camargo, 2013). Furthermore, there is no universally applicable tracking algorithm. This approach has been used and documented in numerous studies (Camargo 2013; Camargo and Zebiak 2002; Walsh et al., 2007), yet despite its limitations it is recognized as a valid approach and is continually being improved.

### 2.7.4 Selecting GCM outputs

As part of the campaign to improve model performance at regional scales, selecting the most appropriate GCM simulations are important in climate modeling, especially when assessing complex weather systems such as TCs. Models are tested and selected based on their ability to realistically simulate regional climate features. For instance, the influence of SPCZ and the ENSO cycle (key influences for TC formation) are fairly represented by a few but not all of the CMIP3 ensembles (Meehl et al., 2007). Individual climate models such as the Goddard Institute for Space Studies ModelE (GISS-ER) and Goddard Institute for Space Studies Atmosphere–Ocean Model (GISS–AOM) produce poor results after simulating the behaviour of the ENSO cycle while the Institute of Numerical Mathematics Coupled Model Version 3.0
(INM-CM3.0) and GISS-ER struggle to realistically simulate SPCZ, surface air temperature, and the West Pacific Monsoon, let alone the influence of ENSO on TC activity in the SPO (Irving et al., 2011). Using multiple climate models is vital for identifying the appropriate simulated datasets out of a group such as the CMIP3 for a specific region. Significant improvements have recently been documented for GCM simulations as computing power increases and through using parameterization (representing physical processes at smaller scales in climate models) (Lupo & Kininmonth, 2008).

2.8 Future behaviour of TC activity under warming climate

The future behaviour of TCs in a warming environment has been investigated at regional and global scales with diverse conclusions. Using dynamical downscaling, Nguyen and Walsh (2001) concluded that geographical distribution and variations of TC activity in the SPO will be influenced by El Niño events and that this pattern is likely to continue in a warmer climate. In other experiments, the global frequency of TCs is found to either decrease (Knutson et al., 2010; Oouchi et al., 2006; Yokoi & Takayabu, 2009; Sugi et al., 2010) or stay the same (Knutson et al., 2010) in agreement with regional simulations for the SPO by the end of the 21st century (Nguyen & Walsh, 2001). This agrees with statistically downscaled results that future TC index (GP) indicates a decrease in conducive environment for TC activity using both CMIP3 and CMIP5 model outputs (Australian Bureau of Meteorology and CSIRO 2011b; Camargo 2013; Emanuel 2013; Emanuel et al., 2008). Furthermore, a similar trend is found with moderate confidence within the domain 0–35°S; 130°E–130°W under three IPCC emission scenarios: B1 (low), A1B (medium), and A2 (high) (Meehl et al., 2007; Zhao et al., 2009). According to a very–high–resolution model experiment, this trend is possible and attributed to an increase in both dry static stability in the tropical troposphere and convective heating (tropical precipitation), as these two factors are significant in reducing the tropospheric overturning circulation (Sugi et al., 2002). Though global frequency of TC activity is projected to decrease for the South Pacific, regions such as the North Atlantic are expected to see the number of TCs increase in a warming environment (Meehl et al., 2007).

Moreover, numerous studies show a global increase in the average number of intense TCs by the late 21st century. Different models with resolutions of 50–100 kilometers predict an increase of intense TCs in a warmer environment both at global and regional scales, particularly over PICs and other regions (Australian Bureau of Meteorology & CSIRO, 2013b).
2011a; Emanuel, 2013; Emanuel et al., 2008; Knutson et al., 2010; Meehl et al., 2007; McDonald et al., 2005; Nguyen & Walsh, 2001). In contrast, other experiments find that there will be no significant changes in the global intensity of TCs but that the precipitation associated with TCs will increase, and these studies further concluded that regional changes rely on variations in SST (Chauvin et al., 2006; Yoshimura et al., 2006). Other experiments predict a slight decrease in medium–intensity storms in a warmer climate (Bengtsson et al., 2006). According to a high–resolution model of 6–km grid spacing, an increase of intense TCs occurs in an enhanced CO₂ environment when average tropical conditions from nine GCMs are used (Knutson & Tuleya, 2004). While most experiments make predictions on a global scale, Nguyen and Walsh (2001) experiment predicted that a warming climate will produce a high frequency of TCs over the southwest Pacific and the Australian region by the late 21st century. These diverse results require more clarity that may be obtained by developing improved methods. Uncertainty about future TC behaviour in general is not only related to coarse resolution in climate models (Yoshimura et al., 2006), but also to uncertainty about the future behaviour of the ENSO cycle in regions such as the SP (Walsh, 2004).

2.9 The approach in this study

This study uses a statistical downscaling technique to better understand both the present and future behaviour of TC activity in the South Pacific. This method was selected because it is less computationally expensive. In addition, application of statistical downscaling in present climate was successful in the North Atlantic basin (Bruyère et al., 2012), so it is reasonable to test this technique in the SP basin. This study applies two TC genesis indices to the NCEP/NCAR reanalysis dataset and CCSM3 climate output to examine observed and future behaviour of TCs in the SP. The climatology of TCs in the SP was first examined to provide variations in observational TC activity over the past three decades. In contrast to earlier methods and techniques, this study carefully examined the ability of GP (Emanuel and Nolan 2004) and CGI (Bruyère et al., 2012) to explain TC activity in the region. Though these indices are universally recognized and tested at global scales and seasonal timescales, their skill in reproducing observations within the SP basin at interannual timescales is unknown.
CHAPTER 3 METHODS AND DATASETS

This research project required 18 months of data analysis and recording. Ninety percent of the data analysis was carried out during a nine–months visit (May 2013–February 2014) at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, USA. NCAR provided the facilities and resources necessary for this research, and the second half of the time was spent writing at the USP Laucala campus. All results were obtained by analyzing existing datasets using the NCAR Command Language (NCL). NCL is a free, open source programming tool for accessing, analyzing, and visualizing datasets in numerous formats (Mini-Language Reference, 2013). This study was therefore completed in collaboration between NCAR and the Pacific Centre for Environment and Sustainable Development (PACE–SD) at USP.

This chapter provides a detailed description and explanation of the study area, applied datasets, and data analysis procedures.

3.1 Study area

3.1.1 Definition of SP and impacted population

This study focuses on TC activity in the South Pacific tropical cyclone basin. The study area covers the sub–region of the SPO 0–30°S, 160°E–120°W (Figure 9) as officially defined by the WMO (WMO, 2011). It encloses thousands of islands and atolls that are part of more than 8 Pacific Island Countries (PICs), namely Cook Islands, Fiji, Kiribati, Nauru, PNG, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu . The majority of people in these PICs reside along coastlines and depend mostly on agriculture and marine resources for food and income (Terry, 2010). Therefore, they have robust connections with the physical environment for sustenance, cultural practices, traditional medications, and their livelihoods, developed over centuries. Apart from socio–economic challenges such as unemployment, deprived economy, political instability and education, island residents are experiencing changes in climate such as shifting rainfall patterns, higher temperatures, sea level rise, and alteration in the frequency of extreme events (Australian Bureau of Meteorology & CSIRO, 2011a). This has detrimental effects on both the physical and human environments over time. PICs are highly vulnerable to the direct and indirect impacts of TC activity (Terry, 2010; WMO, 2011). This study covers the PICs that are vulnerable to the impacts of TC activity.
3.1.2 Climate of SP basin

Weather patterns in this region are affected by three regional climate phenomena involving wind convergence and rainfall, namely the Intertropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), and the West Pacific Monsoon (WPM). Variations in seasonal rainfall and climate in the Federated States of Micronesia (FSM), Kiribati, Nauru, Palau, Marshall Islands, and Papua New Guinea (PNG) are deeply affected by the ITCZ and the WPM while rainfall over Cook Islands, Samoa, Fiji, Solomon Islands, Vanuatu, Kiribati, and Tuvalu is attributed to the SPCZ and changes in its position (Australian Bureau of Meteorology & CSIRO, 2011a). Furthermore, precipitation is higher in the western region than the eastern side (Figure 11 demonstrates these sides) in normal climate conditions because of the persistent easterly trade winds pushing warm water toward the western side and further into the Australian Sea—resulting in more convections in that area (Australian Bureau of Meteorology & CSIRO, 2011b). Furthermore, the ENSO cycle has a great influence on the normal climate condition. In the warm phase, the normal condition has the opposite effect as easterly trade winds relax while the warm phase is an enhanced weather pattern of the normal climate condition (Terry, 2010). Large–scale features and climate variability therefore are significant to variations in the region’s seasonal rainfall and temperatures.

Heavy rainfall, tropical cyclones, heat waves, droughts, and storm surges are also common extreme weather patterns affecting certain PICs. TC activity in particular is the main focus as it brings destructive winds, heavy rainfall, storm surges, and other related adverse impacts on economic activity (Terry, 2010). Chapter 2 above discussed the influence of regional climate phenomena on TC activity in the SP basin.
3.2 Datasets

Three different datasets are used in this study: observed TC activity for the SPO and records of Oceanic Niño Index (ONI) values across the equatorial Pacific, reanalysis datasets, and global climate model output. Each dataset is described in sequence below.

3.2.1 SPEArTC

The Southwest Pacific Enhanced Archive for Tropical Cyclone (SPEArTC) was selected from four available best track datasets. Previous studies used historical records from the JTWC, IBTrACs, and the Southern Hemisphere Tropical Cyclone Data Portal—all of which are freely available datasets—for TC activity and related studies in the SPO (Australian Bureau of Meteorology & CSIRO, 2011a; Basher & Zheng, 1995; Chand & Walsh, 2009; Hastings, 1990). This study employs the SPEArTC dataset to assess the level of observed TC activity in the SP basin. SPEArTC is a newly developed dataset that runs from 1841 to present, but this study concentrates on observations from 1981–2010 because high-quality Southern Hemisphere observations began in the early 1980s (Diamond et al., 2012). SPEArTC is an optimized version of IBTrACs, the universal database of observed TCs in all cyclone basins. Observations are homogeneous with a common data format and follow the 10–minute wind averaging standard as recommended by WMO (Harper et al., 2008). Essentially, the SPEArTC dataset has all the qualities attributed to IBTrACs, and the main improvement is the removal of duplicate records and the inclusion of tracks that were not
previously recorded for the SPO (Diamond et al., 2012). Based on these improvements, the SPEArTC best track is used for this study.

**3.2.2 NCEP/NCAR Reanalysis 2**

This study employs the NCEP/NCAR reanalysis dataset to provide information about the recent climate of the SP basin. The NCEP/NCAR reanalysis dataset is a 40–year modeled dataset that provides the best estimate of the state of the atmosphere over the Earth’s surface. Reanalysis is a technique that enables scientists to develop a complete global record of variations in weather and climate over time from the Earth’s surface to above the stratosphere—yielding meteorological data in all locations through a process known as *data assimilation* (Kalnay et al., 1996). The NCEP/NCAR reanalysis uses a global data assimilation system and numerical prediction model with horizontal resolution of approximately 210 kilometres. This database was created using many sources of observational records (land surface, rawinsonde, ship, pibal, aircraft, and satellite) from various institutions and countries with an assimilation system that is designed with quality controlled and monitoring techniques that produces 1 month of reanalysis per one standardized “clock” day on a CRAY YMP/8 supercomputer. Reanalysis data is thereby free from possible climate jumps related to any changes in the data assimilation system (Kalnay et al., 1996). Different output variables are available for different needs, and it includes a common atmospheric field, information on the top–of–the–atmosphere, and isentropic fields. The NCEP/NCAR Reanalysis 2 is the updated version of the NCEP/NCAR Reanalysis 1.

To meet the study requirements, a relevant dataset was extracted from the NCEP/NCAR reanalysis output and presented on a monthly timescale. This data subset consists of relative humidity, absolute vorticity, vertical wind shear, and SST. Furthermore, potential intensity (Bister & Emanuel, 1998), GP (Emanuel & Nolan, 2004), and CGI (Bruyère et al., 2012) were computed as additional variables over the period 1981–2010. It is also worthy to note that all the above mentioned variables were normalized and scaled to be dimensionless and also to ensure they are all relatively similar so that any one variable is not more important than others. Furthermore, because vertical wind shear possess an inversely proportional relationship with a favorable environment for TC formation (Gray, 1975), the normalizing approach has allowed a directly proportional relationship for consistency in the computation of correlation (see sub–section 3.3.2). The reanalysis was used to represent the state of recent climate because comprehensive observed meteorological data for the SP basin did not exist.
According to Bruyère et al., (2012), both the European Centre for Medium–Range Weather Forecasts (ECMWF) and NCEP/NCAR reanalysis sufficiently represent the recent climate in the North Atlantic. In the present study the NCEP/NCAR reanalysis data was selected because it is the most readily and available resource at NCAR. The usefulness of the reanalysis datasets in North Atlantic basin assumes that both are also adequate to study the climate of other regions of the planet including the South Pacific. This assumption is based on the foundation that the product of all necessary climatological conditions (coriolis parameter, low–level relative vorticity, weak tropospheric vertical shear, ocean thermal energy temperature greater than 26°C at a depth of 60 meters, conditional instability and improved lower tropospheric relative humidity in the mid–troposphere) are useful to explain long–term seasonal frequency of TC formation in all locations per seasonal timescale (Gray, 1998; Gray, 1968).

### 3.2.3 Community Climate System Model output

Future climate information was downscaled from a GCM known as the Community Climate System Model version 3 (CCSM3) (Collins & Bitz, 2006) that was developed and maintained by NCAR. This version is an example of a coupled global climate model and represents the atmosphere, ocean, land surface, and sea ice. These components are linked by a flux coupler that allows exchange of climatic variables. It is designed to provide simulated climate data at all spatial locations on the planet. Unlike previous versions 1 and 2, CCSM3 is enhanced for climate–change simulations with a T85 grid for both the atmosphere and land, and approximately 1° resolution for the atmosphere and land, and for both the ocean and sea ice. This system incorporates further improvements in its physical parameterizations to minimize systematic errors, including a new treatment of cloud processes, radiative forcing, aerosol, ocean mixed layers, atmospheric fluxes, and sea–ice dynamics (Collins & Bitz, 2006). However, there remains systematic error in representing ENSO variations, ocean–atmosphere fluxes in coastal regions, distribution of precipitation in the tropics, and continental surface air temperature. The output is generated for past, current, and future climate under a range of emission scenarios (Collins & Bitz, 2006). The CCSM output was bias corrected prior to being applied in this study. GCMs are known to suffer from a wide range of systematic errors, so a bias–correction method was used to correct the mean error while maintaining the weather variance, climate variability, and
climate change in the model (Bruyère et al., 2013; Done et al., 2013). To illustrate the success of this bias–correction method in high–impact weather, tropical cyclones in the North Atlantic and precipitation over North America are shown to be well captured using downscaled bias–corrected CCSM3 data (Bruyère et al., 2013). Because of that, the CCSM3 simulation was chosen for this study. Detailed information on the bias–correction method appears in the methods sections of recent studies by Done et al., (2013) and Bruyère et al., (2013). The specific data used in this study was again extracted from the parent CCSM output generated under the IPCC A2 emission scenario and presented on a yearly basis from 1980 to 2099. Similar to the reanalysis dataset, the future simulation dataset has GP, CGI, potential intensity, vertical wind shear, relative humidity, and vorticity. These variables (dataset) are normalized and used in the downscaling of TC activity in the SP.

3.2.4 Oceanic Niño Index (ONI)

The Oceanic Niño Index (ONI) was used to determine the correlation between ENSO and the spatial distribution of TC activity across the tropical Pacific. The ONI is a three–month running mean of SST anomalies in the Niño 3.4 region (Figure 10). SST anomalies of +0.5°C and above indicate El Niño seasons, while those of -0.5°C and below indicate the cold (La Niña) phase of the ENSO cycle. The neutral phase is represented by ONI values between +0.5°C and -0.5°C (NOAA, 2014; Null, 2014). When assessing the distribution of TC activity, preceding studies employed different indices. For instance, Kuleshov (2012) used the Southern Oscillation index (SOI) in his study. In contrast, the current study uses ONI values to assess the response of TC activity to climate variability across the region. First, it avoids repetition of Kuleshov’s (2012) method and also it strives to test the ability of ONI in capturing climate variability across the equatorial Pacific.
3.3 Data analysis procedure

3.3.1 Assessing observed TC activity

Assessment of observed TCs is based on variations in genesis location, frequency, tracks, and intensity on different timescales. Genesis location was assessed on a decadal timescale to locate the first geographical coordinates (the first track point) of the observed TC events in the region to provide information on decadal shifts across the equatorial Pacific. Furthermore, TC tracks and TC frequency were analyzed separately for the SPO and the SP basin to determine the number of TCs recorded in the study area every 10 years (refer to Appendix A3 for detailed explanation). The frequency of recorded TC events of Categories 1, 2, 3, 4 and 5 (using the conventions of the Australian Tropical Cyclone Intensity Scale—see Appendix A3) was also examined to identify the most and least–frequently occurring intensities, then Category 3, 4, and 5 events in the SPO were further analyzed (Fiji Meteorological Service, 2014). Moreover, the spatial distribution of TC events was assessed against the ONI values to examine the impact posed by climate variability across the equatorial Pacific. This climatological assessment only considered observations in the period 1998–2010 because quality control of recording (satellite era) for this region of the globe began early in the 1980s (Landsea et al., 2004).

Finally, the interannual frequency of TCs in the entire SPO was computed to illustrate variations in observed TC activity and used for verification of the indices in recent climate.
While this study is restricted to the SP basin domain, a more thorough study would include observations throughout the entire SPO (outside the SP basin) to understand contributions of individual large–scale environmental factors to TC development in the SP basin. Therefore, observations in the southwest Pacific as defined by Diamond et al., (2012) were used in the computation of the annual frequency of TCs, since they showed that most TC tracks recorded over the PICs and territory originated from the Australia Sea, and some ended up as extra–tropical cyclones further south.

3.3.2 Curve–fitting exercise

TC genesis indices were applied to the NCEP/NCAR reanalysis data to illustrate their performance in the SP basin. Averaged values of GP, CGI, and all the predictors for the months of December, January, and February (DJF) were used in this study based on the conclusion by Camargo et al., (2007b) that these have been the peak months of the November–April cyclone season over the tropical region 0°–40°S, 180°–110°W. These indices were applied over the domain 0–30°S, 165°E–120°W to verify their skill in reproducing the annual frequency of TC activity in the period 1981–2010. Individual predictors were also tested to illustrate their contribution toward the overall performance of the genesis indices and to determine how well they account for variations of TC activity in recent climate. This is accomplished by comparing the annual frequency of observed TCs with predictions by each of the variables. Their skill is quantitatively assessed by computing the $r^2$ values (the square of the linear correlation coefficient). This study refers to this method as “curve–fitting exercises.”

3.3.3 Averaging regions over the SP basin

In an attempt to improve the TC genesis indices, the SP basin was divided into equal halves called the eastern and the western part of the basin (Figure 11). There is no theoretical support for this approach, but the justification arises from the importance of the Main Development Region (MDR) in the North Atlantic. MDR refers to a portion of the entire basin that accounts for higher genesis activity in the North Atlantic (Bruyère et al., 2012), hence the supposition is that the SP basin should have its own MDR. In addition, the notion of using Empirical Orthogonal Function (EOF) analysis to describe the form of climate variability affecting TC activity in the SP is a contributing factor towards partitioning the basin into sub domains (Benestad et al., 2007). This analysis would typically have some
associated scale that is probably smaller than the entire basin. It is possible that the ideal size to detect signals in TCs would correspond to the size of these EOFs (Benestad et al., 2007; Shea, 2013). Division of the SP basin resulted in two sub-basins known as the western (0–30°S, 160°E–160°W) and the eastern (0–30°S, 160°W–120°W) parts of the basin (Figure 11). An independent data mining (see discussion below) exercise agreed with this approach of identifying the eastern part of the basin particularly the domain 10°N–30°S, 150°W–70°W as a possible MDR in the SPO (Bruyère, 2014). The data mining region is important and called ‘hotspot’ in this study. In summary, the current study has the following domains; SP basin, eastern part and the western part, and the data mining region which is also known as the hotspot to genesis activity in the SPO (see sub-section 3.4.4 and Chapter 5 for a detailed explanation of the averaging region and the hotspot).

![Figure 11. Map showing the SP basin divided into eastern and western halves.](image)

The data mining method aims to evaluate the effectiveness of existing genesis indices namely CGI (Bruyère et al., 2012) and GP (Emanuel & Nolan, 2004) as proxies for interannual frequency of observed TC over all the cyclone basins across the planet. According to Bruyère (2014), the index components were applied at each grid point of the NCEP/NCAR reanalysis and then correlated with the annual frequency of TC in each basin. Further information about the data mining method can be accessed via (Bruyère, 2014). The finding for the SP basin
was then recognized as the hotspot in this study. In addition, there is no theoretical substance for selecting that region as the hotspot but the performance of the cyclone indices is better for the eastern part of the equatorial Pacific and is improving for the hotspot region as they are overlapping (Figure 22). It is also vital to bear that existing cyclone indices has never being attested for the SP cyclone basin and the approach to prove their performance in this study is a relevant beginning for tropical cyclone modeling in the South Pacific.

3.3.4 Applying indices and index components over the averaging regions

The tropical cyclone indices and all the index components were selectively applied to the reanalysis data over the averaging regions. GP and CGI were tested over the SP basin, the sub–domains, and the hotspot area. Because of the poor performance by potential intensity, wind shear, relative humidity, and absolute vorticity in the SP basin and the sub–domains, this study has only considered their application over the hotspot region. Selecting the hotspot region is because MDR has revealed effective seasonal forecasting techniques and significant role in differentiation of historical variability of TC across the North Atlantic basin (Bruyère et al., 2012; Elsner et al., 2006; Gray, 1984; Klotzbach, 2011). The research is expecting a similar case for the South Pacific. The curve–fitting exercise was then used to assess the level of skill displayed for the period 1981–2010.

3.3.5 Downscaling future climate

Future climate is statistically downscale from the CCSM3 output for the period 1981–2099. The averaged values for GP and CGI were applied only over the hotspot region to extract information on future TC activity in the PICs. Furthermore, individual normalized predictors (potential intensity, vertical wind shear, and relative humidity) were also downscaled to estimate their individual contributions. The idea of downscaling individual factors is based on the fact that TC activity is still not realistic in CMIP3 and even CMIP5 model, even though they are not better predictors of TC frequency (Camargo, 2013). This study uses a simple calculation to assess future percentage trends in TC frequency by dividing the linear trend by the average value for the period 1981–2099 and multiplying by 100.
CHAPTER 4 RESULTS

The findings of this study are organized into four sub–sections: the climatology of TC activity in the SP, verification of the two TC genesis indices, performance by individual predictors, and the statistical downscaling of the future climate for the SP basin.

4.1 Climatology of TCs in the SP

The findings are based on historical observational records in the SPEArTC best track dataset. This dataset includes genesis location, storm tracks and intensity, spatial distribution of TC relative to the ONI values, and the annual frequency of storms during the period 1981–2010. Each TC metric is examined on decadal and interannual bases to demonstrate changes and observed variations and distribution across the equatorial Pacific.

4.1.1 Genesis location

![Figure 12. Genesis locations of observed TCs in the SP basin as recorded in the SPEArTC dataset from 1981–2010. Spatial distribution of genesis locations are presented on decadal timescales as shown in (A) 1981–1990, (B) 1991–2000, (C) 2001–2010, and (D) all three decades (1981–2010).](image-url)
TC genesis locations are spread across the basin. Genesis locations mark the first recorded point (latitude and longitude) where TCs were observed in the SPO (Figure 12). Based on the three decadal time scales, more TCs were recorded in the western part of the basin (0–30°S, 160°E–160°W), and further inside the Australian sea (0–30°S, 150°E–160°E) than in the eastern side of the region (0–30°S, 160°W–120°W). Similarly, few genesis locations were recorded between 30°S and 40°S in the eastern half of the basin (Figure 12). The recent decade (2001–2010) has fewer genesis locations than the first two decades (1981–2000). It is clear that spatial distribution of genesis locations vary across the basin, with the majority centered over the western part of the SP during the period 1981–2010.

4.1.2 TC tracks and counts

![Storm tracks and counts](image)

**Figure 13.** Storm tracks and counts on decadal timescale in the SPO as recorded in the SPEArTC best track dataset during the period of (A) 1981–1990, (B) 1991–2000, (C) 2001–2010 and (D) 1981–2010.
The number of TCs recorded in the SP basin is evidently decreasing on a decadal basis. During 1981–1990, 144 TCs were observed in the SPO; 86 of these occurred in the SP basin domain. During 1991–2000, 146 TCs were observed in the SPO and 77 of these were recorded within the basin domain. In the recent decade, 103 TCs were recorded in the SPO and 51 TCs were noted inside the basin domain. During these three decades (1980–2010), the SP basin domain had 214 of the 393 TCs recorded inside SPO. Besides that, TCs have shown different pathways on a decadal basis. In the first two decades, tracks are widely spread with the greatest spread in the 1990s, while TCs within the recent decade are confined to a smaller region. Moreover, there have been few genesis locations or tracks recorded at latitudes 0–5°S (Figures 12 and 13) in the past three decades. In summary, while the number of tropical cyclones decreased on a decadal basis, spatial distribution of TC activity varies across the basin.

4.1.3 ONI values and distribution of TC events

The Oceanic Niño Index (ONI) shows a noticeable influence on the spread of TC activity across the basin (Figure 14). TC tracks shift farther toward the eastern side when ONI values are ≥+0.5°C. In contrast, TC tracks favor the western part of the basin–even toward northeast Australia–when ONI values are ≤−0.5°C. When ONI values are <0.5°C and >−0.5°C, the spatial distribution of TC tracks is fairly centered across the equatorial
Pacific. Furthermore, the spatial distribution of genesis location is also linked with the peak annual average frequency of observed TCs across the equatorial Pacific. Therefore, this index has a substantial influence on the spatial distribution of TCs in the region.

4.1.4 TC tracks and changes in intensity

Spatial distribution of tropical cyclone intensity varies across the SP basin. Based on the Australian Intensity Scale, Category 4 and 5 hurricanes (severe tropical cyclones) were recorded particularly in the western and central part of the basin (Figure 15). In contrast, Category 1, 2, and 3 TCs are evenly recorded in both the western and eastern sides.

Figure 15. Distribution of TC tracks with changes in intensity on a decadal timescale. Distributions are shown during the periods (a) 1980s, (b) 1990s, (c) 2000s, and (d) 1981–2010. Blue, pink, green, orange, and red colors represent Categories 1, 2, 3, 4, and 5 respectively on the Australian and SP TC intensity scale.
4.1.5 Frequency of TC intensity

Most TCs reached Categories 1–4 (most frequent categories) during the period 1981–2010 on the Australian intensity scale. Figure 16 shows wind speeds of 30–65 knots as the most common intensity in the SP. Category 5 TCs were rarely recorded, at around 2.5% of total events. The recent decade saw more severe TCs than the 1980s–1990s.

![Frequency of maximum wind speed](image)

**Figure 16.** Frequency of observed 10-minute-averaged wind speed on a decadal timescale in the SP. The number of times a particular wind speed was recorded is shown in (A) for the 1980s, (B) for the 1990s, (C) for the recent decade, and (D) for the entire period 1981–2010. TC categories are based on the Australian Intensity Scale. (Note: The frequency scale is different for each graph).

4.1.6 Trend of TC category

On a decadal timescale, the trend of TC categories is varying. Category 1–3 TCs on the Australian TC intensity Scale have shown decadal variations over the three decades. During the first decade (1981–1990), Category 1–3 TCs slightly increase and then decrease in the next two decades (1991–2010). In contrast, Category 4 and 5 TCs show a slight increase over the whole period 1981–2010 (Figure 17).
4.1.7 Annual frequency of TCs

The frequency of TCs varies on an interannual time scale over the 30–year period. During the first two decades (1981–2000), the historical record shows extensive variation. In contrast, there is a considerable decrease in variation during the recent decade (2001–2010). Two periods of high TC activity were recorded in 1993–1994 and 1997–1998 with an annual frequency of more than 30 and about 26 TCs, respectively (Figure 18). The years with the lowest TC frequencies over the three–decade period were observed around 1990 and 1995. Furthermore, Figure 15 clearly shows that the average frequency of TC occurrence ranges between 10 and 15 on a yearly basis, and that there has been no year recorded without a tropical cyclone event.

Figure 17. Line graph showing variations and trends in observed TCs in the SPO during the three decades from 1981–2010.
4.2 Verification of TC genesis indices

The performance of GP and CGI when applied to the NCEP/NCAR reanalysis dataset is presented below. The analysis begins with predictions by the TC indices, and then explores individual predictors in the main genesis activity region of the SP basin.

4.2.1 Prediction by GP over the SP domain

GP fails to capture the observed interannual frequency of TCs over the entire SP basin (0–30°S, 160°E–120°W). The curve–fitting exercise reveals that GP inaccurately predicts the lowest TC occurrences around the periods 1982–1983 and 1995–1996, (Figure 19A). The lowest GP prediction is far below the minimum observation (about 9) during the entire three decades. Besides that, it over–predicts the interannual frequency by about 39 and 37 TCs during the periods 1984–1985 and 1994–1995, respectively. An annual frequency of 11–12 TCs was observed during these periods. GP’s overestimation exceeds the maximum observation which is no more than 30 TCs around 1993–1994 and during 1981–2010, the second highest in the historical record. Furthermore, GP fails to capture the observed decreasing number of TCs during 1996–2010. GP therefore fails to capture the overall variation and spatial distributions of TC activity in the region.
Figure 19. Performance of GP and CGI when applied over the entire SP basin during the period 1981–2010. (A) Shows GP skill and (B) shows CGI skill. The $r^2$ value for GP and observation is shown in (C), while that $r^2$ value for CGI is shown in (D).

4.2.2 Prediction by CGI over the SP

CGI struggles to capture the interannual frequency of storms in the SP basin (0–30°S, 145°E–120°W). To illustrate, it predicts about 29 and 39 tropical storms during 1992–93 and 1997–1998, years that recorded 19 and 21 tropical storms, respectively (Figure 19B). Similar to GP, this overestimation reaches 39 tropical storms. Furthermore, CGI prediction departs from the observed decreasing trend during 1996–2010, but it does produce a sudden decline in 2008. It struggles to capture the decrease in TC activity recorded around the period 1995–1996. In summary, CGI is unable to replicate the observed interannual variations as it both underestimates and overestimates interannual variations in the SP.

CGI shows better skill than GP when applied over the entire SP basin. Though both genesis indices show poor skill, CGI tends to perform better than GP by providing reasonable skill in mimicking the observed interannual variations. For instance, CGI to some extent predicts the
second–highest year of genesis activity, while GP does not. It overestimates an increase in TC activity from 2000–2010 while GP severely overestimates that event. Statistically, there is a positive correlation with a variance explained of $r^2=0.03$ (Figure 19D). In contrast, GP shows a negative correlation between observations and its own predictions (Figure 19C). In summary, CGI performs marginally better than GP.

### 4.2.3 Performance over sub-regions

To improve the skill of GP and CGI, the basin was divided into halves. This approach creates the western part (0–30°S, 160°E–160°W) and the eastern part (0–30°S, 160°W–120°W) of the SP basin as described above. Each TC index was applied to the NCEP/NCAR reanalysis data and compared with the entire annual frequency of TC events in the SPO (0–40°S, 135°E–120°W). Skill varies per index in each averaging region.

![Figure 20](image)

**Figure 20.** Performance of GP and CGI when applied over the western part of the SP basin during the period 1981–2010. GP skill is shown in (A), and CGI skill is shown in (B). The $r^2$ values for GP and observations are shown in (C), while those values for CGI are shown in (D).

In the western part (Figure 20), both indices fail to predict the observed TC activity during the entire period of study. As shown in Figure 20A, GP lacks the skill to reproduce the
observed annual frequency of TCs in the region 0–40°S, 135°E–120°W as it does over the entire SP domain. The negative correlation between the observed and predicted number of TCs is shown in the scatter plot (Figure 20C). Similarly, CGI fails to reproduce the observed annual frequency of TCs. Skill demonstrated in the western part of the basin is weaker than the predictions over the entire SP basin. In summary, GP and CGI fail to simulate the observed variations in TC during the period 1981–2010 when applied in the NCEP/NCAR reanalysis dataset over the domain 0–30°S, 160°E–160°W.

**Figure 21.** Performance of GP and CGI when applied over the eastern part of the SP basin during the period 1981–2010. Skill by GP is shown in (A), and CGI skill is shown in (B). The $r^2$ values for GP and observations are shown in (C), while those for CGI are shown in (D).

In the eastern part, the TC genesis indices improve their overall skill. GP demonstrates improved skill in reproducing the general variations in annual frequency of TCs when applied over the eastern part of the basin. It mimics the general observed variations in the 1980s and 1990s. However, it overestimates the second–highest occurrence of TCs during the period 1997–1998 and further struggles to capture the overall general variation pattern in the recent decade (Figure 21A). This improved performance is demonstrated by an $r^2$ value of 0.09 (Figure 21C).
Furthermore, CGI’s performance is also improved when applied over the eastern part of the SP basin. It demonstrates improved skill for the last two decades by reproducing the overall observed variations of TC frequency. However, it overestimates the second–highest occurrence of TC activity during the period 1997–1998, and it struggles to simulate observations in the 1980s and the peak period of TC activity in 1993–1994 (Figure 21B). There is an improved correlation between the CGI prediction and observation with an $r^2$ value of 0.15 (Figure 21D). In summary, dividing the basin into eastern and western parts led to improved skill demonstrated by GP and CGI, and applying the TC genesis indices over the eastern part of the basin resulted in an improved performance compared to the western part (0–30°S, 160°E–160°W) and the entire basin (0–30°S, 160°E–120°W).

4.2.4 Defining a key region of genesis development

The previous subsection showed that applying genesis indices to the eastern part of the SP basin performed better than applying them over the entire basin. This section further explores

**Figure 22.** Map showing the averaging regions. The SP basin is enclosed with yellow lines and is divided into western and eastern parts. The data–mining domain (hotspot) is surrounded by an orange line.
region refinement. According to Bruyère (2014), a possible region of TC development and formation for the SP region is the domain 10°N–30°S, 150°W–70°W, found via a data mining approach. Detailed information about the data mining approach appears in Bruyère (2014). The eastern part of the basin is contained within this data–mined region, but the western region is excluded (Figure 22). Based on the results presented earlier along with the hot spot region identified in Bruyère (2014), verification of the TC genesis indices, individual predictors, and statistical downscaling of the future climate data are applied over that region and the results are presented below.

### 4.2.5 Performance over the hot spot region

![Image](image_url)

**Figure 23.** Skill demonstrated by TC genesis indices over the MDR sub–region. Observed annual frequency of TCs (blue), prediction by the genesis indices (red), and scatter plots with $R^2$ values. Prediction by GP is shown in (A), and prediction by CGI is shown in (B). The $r^2$ values relating observation and prediction are shown in (C) for GP, and in (D) for CGI.

GP and CGI show their optimum skill in capturing the observed variations of TC frequency in the SP basin only when they are applied over the domain (10°N–30°S, 150°W–70°W). GP further enhanced its skill over the three–decade period (Figure 23). Although it fails to
realistically replicate the two peak periods (1993–1994 and 1997–1998), its skill is enhanced to capture the general variations over any of the previous predictions with an $r^2$ value of 0.17 (Figure 23B). Similarly, CGI shows greatly improved skill when applied to the hot spot area with $r^2=0.19$. It tends to capture the observed general variations of TC frequency in the SPO except that it struggles to simulate the two periods of high TC activity, similar to GP (Figure 23B).

In summary, performance of GP and CGI is sensitive to the spatial averaging region. There is a remarkable difference between applying the indices over the SPO as a whole in contrast to the eastern and the main region of tropical cyclogensis that occupies the domain 10°N–30°S, 150°W–70°W. Only when GP and CGI are applied over this region of TC development are the observed variations better predicted.

### 4.3 Performance of the individual predictors

The curve–fitting exercise is used to identify the dominant predictors that drive TC development in the region. The main four large–scale environmental factors are illustrated below, as is their correlation with the observed interannual frequency of TCs in the SP basin. The normalized wind shear shows significant correlation with the observed interannual frequency of TC activity for the period 1995–2010. However, it fails to correlate with the observed peak period (1993–1994) of TC activity in the region. Moreover, the expected correlation overestimates the second highest record of TC activity in 1997–1998. The presence of weak shear correlated with observations during the three–decade period is statistically noted with $r^2=0.19$ (Figure 24).

Although the normalized potential intensity has a moderate correlation with the observed variations, the expected correlation fails to match the overall variations in the first decade and overestimates the second–highest period of TC activity in 1997–1998. Even the general decrease in the recent decade (2001–2010) is captured, potential intensity does not effectively correlate with the exact number of tropical cyclones. The correlation between potential intensity and observed TC activity has $r^2=0.12$ (Figure 24).
Figure 24. Normalized large-scale environmental factors in the NCEP/NCAR reanalysis data and observed TC frequency during the last three decades for the SP basin. Normalized wind shear is shown in (A), and its correlation with observed TC frequency is shown in (B). Normalized potential intensity is shown in (C), and its correlation with observed TC frequency is shown in (D).

Normalized relative humidity demonstrates a low-level correlation with TCs to capture their observed interannual frequency. To illustrate, RH correlation captures the second–highest period (1997–1998) of TC activity (Figure 25) but overestimates the frequency of TCs in the period 1981–1995 and again in 2004–2010. Similarly, it underestimates the observed TC activity recorded in 2001–2002 and fails to account for the highest recorded genesis activity in 1993–1994. Relative humidity can be used to capture observations during the three–decade period, as its correlation is $r^2=0.12$ (Figure 25).

Normalized absolute vorticity demonstrates a superior correlation with the general observed pattern in the last three decades, particularly in the most recent decade (2001–2010). However, it does not correlate closely with the exact frequency of tropical cyclones at an interannual timescale, nor with the highest number of TCs recorded in 1993–1994. The
The correlation of absolute vorticity with the variations in observed TC activity during the three decade period was found to be $r^2=0.17$ (Figure 25).

4.4 Downscaling future climate

TC genesis indices are applied to future climate data to infer the potential future behaviour of TC activity. GP and CGI are applied over the hotspot region to produce the simulation over the SP domain.

4.4.1 TC genesis in future climate

The application of GP and CGI to bias–corrected CCSM climate data over the MDR indicates a decreasing trend over the SP basin. GP predicts about a 41% decline while CGI predicts a 5% decline. Furthermore, the simulated GP values have extensive variations with a highest value of 0.4 and a lowest of 0.15 for the period 2020–2100 on a decadal timescale. The pattern in variations of GP values as of 2060–2100, however, ranges between values of 0.15–
0.25 (Figure 26A). CGI has greater variability for the period 2020–2100 within the range of 0.012–0.03, with highest values of 0.034 and 0.038 respectively around 2060 and 2080 (Figure 26B).

![GP and CGI applied in CCSM output](image)

**Figure 26.** GP and CGI applied to the bias–corrected CCSM climate output from 1980–2100 under the A2 emission scenario. GP prediction is shown in (A) while CGI is shown in (B).

### 4.4.2 Future behaviour of predictors

Individual predictors show different levels of contribution to future annual TC activity by the 21st century. All the large–scale environmental variables show a decreasing trend in the bias–corrected CCSM output. Potential intensity, absolute vorticity, relative humidity, and wind shear are likely to be decreased by 15%, 1.3%, 4.6%, and 5%, respectively (Figure 27).
Figure 27. Contributions to future predictions by using normalized potential intensity (A), wind shear (B), absolute vorticity (C), and relative humidity (D) as TC predictors in the bias-corrected CCSM output throughout the 21st century.
CHAPTER 5 DISCUSSION/ANALYSIS

This chapter presents detailed interpretations of the findings. Chapter 4 showed that the findings of this research come in two parts: (1) the assessment of observed TC activity and (2) statistical downscaling of future climate over the SP basin. Major findings are that climate variability, such as the extreme phases of the ENSO cycle, has a strong influence on the observed spatial distribution of TC activity across the equatorial Pacific. This section discusses the broader implications of the observed TC activity and the statistically downscaled approach to the CCSM future climate data, and places these results in the context of previous work. Furthermore, it further explains the methods used and some of the shortfalls of the statistical downscaling approach, which could lead to a significant impact on the statistical downscaling technique.

5.1 Spread of genesis location and ENSO cycle

Spatial distribution of genesis locations in the SP is influenced by the ENSO phases. During the neutral phase, the easterly trade wind normally persists to maintain warm surface water from the Pacific Warm Pool around the western part of the basin (Australian Bureau of Meteorology & CSIRO, 2011a; Kuleshov, 2012; Diamond et al., 2013). This is the normal condition across the equatorial Pacific, which maintains both warm surface water and low surface pressure to enhance high convection and precipitation above this region. During a La Niña phase, the easterly trade wind further strengthens and pushes warmer SST to the western end of the basin. In this scenario, the clear implication is that genesis locations are expected only in the western part and not the eastern part since SST fuels TCs (Gray, 1968). In contrast, the easterly trade wind weakens during an El Niño phase, allowing movement of surface warm water eastward to the eastern end of the basin. Genesis locations in the eastern part of the basin are attributed to the El Niño periods, and for this reason locations such as French Polynesia receive TC events during these times (Camargo et al., 2006; Diamond et al., 2013; Kuleshov, 2012). Spread of genesis locations across the equatorial Pacific is therefore strongly influenced by the ENSO cycle.

5.2 ONI index, a reasonable indicator

The ONI index has proved to be a reasonable indicator for the distribution of TC activity under the influence of the extreme phases of ENSO across the equatorial Pacific. The response of storm tracks to the ONI values (Figure 14) indicates that among other indices, the
three–month running mean of SST anomalies provides a sufficient signal for both the ENSO phases and its influence on the spatial distribution of genesis activity in the region. It is also important to note that the present study does not compare neither contrast the performance by ONI index with other indices but it strives not to repeat recent assessments. Take for instance; Kuleshov (2012) was using SOI to assess the origin and distribution of genesis locations in the SPO.

5.3 Position of predictors and spread of TC

The zonal distribution of TC activity across the equatorial Pacific is attributed to the ENSO cycle and the relative positions of observed large–scale environmental factors such as wind shear, potential intensity, relative humidity, and absolute vorticity. The literature records possible explanations for why the distribution of TC activity is influenced by the ENSO cycle.

During an El Niño event for instance, the SST anomalies and relative humidity anomalies at 500 hPa are positive during the TC season over the domain 0–15°S, 160°E–140°W and east of the international dateline between the equator and 10°S respectively, while the negative anomalies are concentrated westward to the Coral Sea of Australia (Kuleshov, 2012). Furthermore, a region of relatively weak vertical wind shear (<8ms⁻¹) is found over the equatorial region and further in the eastern part of the basin. Besides that, negative (cyclonic) vorticity anomalies at low levels are recorded near the equatorial areas, with the minimum centers located at 10°S–175°W, while positive anomalies are recorded at latitudes 15°S–35°S across the basin (Kuleshov, 2012). According to Kuleshov (2012), negative vorticity anomalies over the domain (5°S–15°S) provide an environment conducive for cyclogenesis to enhance TC activity in the eastern part of the basin. The position and nature of these environmental factors are necessary conditions for genesis activity (Basher & Zheng, 1995; Gray, 1968; Kuleshov, 2012; Kuleshov et al., 2009) and during the ENSO warm–phase years, they tend to explain the increase of TC activity in the SP basin. Figures 2 and 3 in chapter 1 demonstrate the position of SST anomalies and weak wind shear in respond to the ENSO phases.

The opposite is observed during La Niña events relative to the occurrence of TCs across the equatorial Pacific. During La Niña years, SST and relative humidity anomalies are positive over the central and western end of the basin to the Coral Sea, while negative anomalies are
dominant farther over the eastern side (Chand & Walsh, 2009; Kuleshov, 2012). The historical record also shows that a zone of weak wind shear (<8ms⁻¹) is situated over the western end with a minimum center at 160°E–175°E. In addition, positive anomalies of vorticity are dominant over the equatorial areas while negative anomalies are recorded southward. Importantly, the occurrence of TC activity in the western part of the basin is consistent with the shift in the location of these conditions during La Niña periods. According to Gray (1968), high SST and relative humidity, vorticity, and relatively weak wind shear are necessary conditions for tropical cyclogenesis. The observed distribution of genesis activity across the region during the two extreme phases of the ENSO cycle is therefore controlled by the large-scale factors; SST, relative humidity, vorticity and wind shear.

5.4 Interannual variability of TC activity

The interannual variation of observed TC activity in the SP is mostly attributed to the extreme phases of the ENSO cycle. The highest genesis activity in the SP was recorded in 1993–1994 when a strong El Niño event occurred across the equatorial Pacific (Australian Bureau of Meteorology, 2011). The second–highest year of TC activity corresponds to the 1997–1998 El Niño event. The influence of the ENSO cycle on the distribution of TC events across the equatorial Pacific has been well documented in the literature (Chand et al., 2013; Diamond et al., 2013; Dowdy et al., 2012; Kuleshov, 2012; Kuleshov et al., 2009; Sinclair, 1994). However, the historical record of TC activity does include a large variation during the 1983–1984 El Niño event, the strongest one recorded during the period 1981–2010. That implies there were other contributing factors such as the position of SPCZ (Vincent et al., 2011) and the influence of an MJO that might have inhibited TC activity during this El Niño period. The spatial distribution of TC activity in the region is therefore not solely determined by El Niño events, as there were other factors that influence the large–scale environment across the region.

There is no long–term trend in the annual frequency of observed TCs in this 30–year period. In the first 20 years, the observed TC frequency was fluctuating, and the two highest–frequency TC events occurred in the 1980s and 1990s. However, the final decade (2000–2010) showed a slight decreasing trend. According to Webster et al., (2005), the number of TCs recorded for a 35–year period was statistically decreasing in the SP basin in an environment of increasing sea surface temperature. However, this slight decrease in the recent decade contradicts with results from Kuleshov et al. (2010) which show no significant
trend in the number of TC in the SPO. This is probably due to a different choice of spatial sub-domain, different Best Track, or differences in methodology. Also note that it is more challenging to discern a long–term relative trend when detailed historical records are limited to 30 years. To establish a statistically significant conclusion, long–term and homogeneous historical data are required (Gray, 1968; Kuleshov, 2012), and this is a disadvantage for the SP as best track control only began in the 1980s.

5.5 Changes in TC intensity

The variation in TC intensity on the decadal assessment seeks more explanations for the SP basin. There is no observed trend in Category 1–3 TCs in the SP basin during the study period (1981–2010) while there a slight increase in Category 4–5 TCs (Figure 17). An increase in intense TCs may be because of warmer equatorial SST that is normally present and further enhanced during cold phases of the ENSO cycle around the western part and in the eastern side of the basin during the warm phases, respectively. This is based on Gray’s (1975) established foundation that SST presumably supplies energy for maintaining TC systems and intensity level. The relationship between SST and hurricane intensity was recorded in the SPO for a 35–years period that warmer SST plays important role in TC intensity and its intensification (Webster et al., 2005). On the same note, the role played by warmer SST to intensify TCs has also been shown in other basins such as the Atlantic (Elsner et al., 2008; Sun et al., 2014). However, the SST argument continues to be controversial among the scientific community and this has resulted in investigating the importance of potential intensity and Tropical Cyclone Heat Potential Intensity (TCHPI). Take for instance, the role of potential intensity was examined to be more important than SST in intensifying TCs in the North Atlantic (Emanuel, 1999; Emanuel, 1986; Holland, 1997) while TCHPI plays significant role in TC intensification for the Western North Pacific (Wada & Usui, 2007). Unfortunately, their application is not tested for the SP basin. On the same note, most of the recent studies have focused on testing SST and its relation to severe TCs, than potential intensity and TCHP (e.g. Elsner et al., 2008 and Sun et al., 2014) let alone in the SP basin. In addition, deficient homogeneous record of observations may hamper long–term historical analysis from producing accurate conclusions about TC intensity for this region of the world. Therefore, to further verify the argument for observed severe TCs in SP basin, more research is required to determine the role of SST, potential intensity, TCHPI and other potential factors contributing to intense hurricanes in this region.
5.6 Identified hotspot

The improved performance of TC genesis indices and individual predictors over the subdomain 10°N–30°S, 150°W–70°W indicates that this region plays an important role in the TC formation and development in the SP basin. This study refers to this region as a “hotspot” for genesis development in the SP cyclone basin. It is likely that this domain shows a robust teleconnection to tropical cyclogenesis in the SP and is possibly due to some sort of atmosphere–oceanic linkage. However, this study does not refer to it as the main development region (MDR) in the SP because the seedlings for TCs have never proven pass through this region. To illustrate, the seedlings in the North Atlantic are the African easterly waves and these actually pass through the sub-domain 10–20°N, 60–15°W hence it is recognized as the MDR (Bruyère et al., 2012). But the ENSO cycle, particularly the warm phase, may be the primary process that causes this linkage in the SP. In contrast, the poor skills shown by GP and CGI when considering the entire basin domain and the western part of the basin indicates that these regions are less important for tropical cyclogenesis in the SP.

This study explored different averaging regions to improve the skill of TC indices in the SP basin and eastern part of the region is significant. A complementary conclusion was made by Bruyère et al., (2014) using a data–mining technique to define the hotspot boundary as 10°N–30°S, 150°W–70°W. Development of cyclones in any given region should not be confused with TC tracks as the development and initiation of tropical storms occurred before the recorded TC track. This approach is successfully applied in the North Atlantic TC basin, with enhanced skill shown by GP and CGI when applied over the MDR, rather than the entire basin (Bruyère et al., 2012), but to some degree in the SP. The response of the genesis indices to averaging regions is attributed to the El Niño seasons whereby distribution and locality of large–scale environmental variables support tropical cyclone genesis and is consistent with historical record (Dowdy et al., 2012; Gray, 1975; Gray, 1968). In summary, the observed interannual frequency of TC activity over the entire SP basin for the time period 1981–2010 can be partly explained by large–scale environmental factors over the hotspot.

5.7 GP vs. CGI

Several important points about the performance of averaging TC indices over sub–regions must be discussed. The indices lack skill in reproducing the observed TC activity when applied over the entire SP basin, and in the western basin. However, such poor performance
does not indicate that GP and CGI cannot predict the observed interannual variability of TC activity in the South Pacific. Although the key reason is a question for further investigation, successful application of these indices was recorded in the recent climate for the North Atlantic basin (Bruyère et al., 2012). This indicates that there may be ways to improve GP and CGI skill in predicting TCs in the SP basin. Over the eastern region of the SP, GP accounts for at least 9 percent of the observed variations while CGI predicts about 15 percent. Over the hotspot region, GP explains at least 17 percent while CGI accounts for 19 percent of the observed interannual variations of TC activity over the entire basin. Obviously, CGI has more skill than GP to predict observed TC frequency in the SP basin. This is possibly because CGI only uses wind shear and potential intensity for its predictions, while GP includes two additional predictors to the equation; absolute vorticity and relative humidity— which may reduce its overall skill. When applied over the hotspot region, this level of skill for GP and CGI is reasonable and may be used to identify major variability and trends from global model datasets (discussion about uncertainties in the statistical tests are presented in section 5.9).

5.8 Examining individual predictors

The performance by normalized individual predictors in the NCEP/NCAR reanalysis dataset signifies individual contributions toward TC activity in the region. Out of the four large–scale environmental factors, wind shear strongly contributed to TC activity as it accounts for at least 19 percent of the variation in the observations during the past three decades. Absolute vorticity accounts for 17 percent, while potential intensity and relative humidity each explain about 12 percent of the interannual variations of observed TC activity. This finding implies that apart from these conducive environmental factors, other climate features could be tested and considered to assess TC activity in the SP region.

Furthermore, correlation by individual predictors indicates how well they contribute to the overall skill by the indices and the challenge in developing one. Weak wind shear is the factor that contributes most strongly to the overall skill and performance of the indices. It is followed by absolute vorticity, while relative humidity and potential intensity are the least influential contributing factors. The explained variance is lower for the SP basin than for the North Atlantic basin (Bruyère et al., 2012). Additionally, that adds to the challenge in developing an empirical relationship (cyclone index) for the SP basin based on these four large–scale environmental variables; the approach pioneered by Gray (1975).
may possibly be caused by errors related to development of the indices or the observational and reanalysis data but such an unsatisfactory finding proved that it was not helpful to develop a regression–based genesis model for the South Pacific with the given resources available. Certainly, the gate is open for further investigation and various methods can be tested.

5.9 Uncertainties related to $r^2$ calculations

The nature of statistical test ($r^2$ calculation) used may denote ambiguous information. To illustrate, the slope of the linear lines fit in Figure 21 C and D was largely determined by few points and performances by all the normalized predictors over the spatial sub–domains were different. According to Benestad et al. (2007), it is reasonable to assume that the calculated correlation is spurious and caused by few outliers to attain coincidence between the variables and observed TC activity. In response, statisticians use statistical significance testing methods to determine the likelihood that a correlation could have occurred by chance (Benestad et al., 2007; Davison & Kuonen, 2010). This process is fairly sophisticated and involves more correlation calculations by taking many random samples from a subset of the distribution of NCEP/NCAR reanalysis dataset—a process known as bootstrapping (Davison & Kuonen, 2010). Indeed, the issue invites more investigations and advanced statistical testing but this is beyond the scope of this study. On one hand, this study is arguing that it is plausible to have physical connections associated with statistical tests in climate studies (Benestad et al., 2007). In summary, while the limitations associated with $r^2$ calculations are respected, the computed weak $r^2$ values are meaningful for the hotspot domain using the NCEP/NCAR reanalysis data. This is a rational justification for the telecommunication or major pattern change such as El Niño event, or synchronization of ENSO and other climate indices such as the Pacific Decadal Oscillation (Wang et al., 2009) could strongly influence genesis activity in the SP basin.

In addition, poor quality data associated with observational TC and reanalysis historical record could be a source of uncertainty in the computed $r^2$ values and the predictors’ performance. To illustrate, low quality meteorological data in PICs may be due to losses of information during recording as a result of missing record, anomalous data and recording errors. Missing data may also occur during processing and archiving via lost records, physical damage and error checking (Basher et al., 1990). Certainly, data recording and processing in PICs were not properly controlled and often affect observational historical record. Poor data
quality may disturb the level of skills shown by the predictors (TC indices and large scale environmental factors) in the current study. The development of SPEArTC is an example of an effort to correct certain errors in missing records with observational TC activity in the South Pacific (Diamond et al., 2012).

5.10 Analysis of future climate

A decreasing trend in TC frequency was found using GP and CGI when applied to the CCSM climate data for the SP basin under a warmer climate. Based on the A2 emission scenario, GP shows a slight decreasing trend while CGI demonstrates a substantial decreasing trend. The percentage decrease varies for the indices because GP uses four large-scale environmental factors: potential intensity, vertical wind shear, relative humidity, and absolute vorticity (Emanuel & Nolan, 2004). In contrast, CGI only uses potential intensity and wind shear (Bruyère et al., 2012) for its prediction. There is a similar conclusions (decreasing trend) made in the previous climate modeling studies that have used both dynamical and statistical downscaling approach (Australian Bureau of Meteorology & CSIRO, 2011b; Camargo, 2013; Emanuel, 2013). The implication of such a result is therefore still limited and future TC activity is a subject for further careful investigation in the SP basin.

Furthermore, GP and CGI do not provide any explicit information on details of a typical TC activity (e.g., intensity, duration, and genesis location) and how these may change in the future. They only indicate that the incidence of favorable environments for TC development is likely to decrease by the end of 21st century. The improved skill of these indices when applied over the hotspot domain in the reanalysis climate data provides sufficient confidence in this prediction and further support similar conclusions by previous studies (Australian Bureau of Meteorology & CSIRO, 2011b; Nguyen & Walsh, 2001).

Analysis of the normalized individual large-scale environmental factors from the CCSM model output indicates the level of future favorable environment for TC activity in the South Pacific. The application of wind shear, vorticity, potential intensity, and relative humidity over the hotspot region has shown a clear indication of a decrease in genesis activity. Knowing that these predictors are necessary conditions for the development of TC activity (Gray, 1975; Gray, 1968), individual predictors can be used to determine the likely behaviour of future climate from GCM output. Since potential intensity, relative humidity, and absolute vorticity have a directly proportional correlation with the development of TC activity
(DeMaria, 1996; Gray, 1968; Gray, 1975), the decrease of these factors indicates a decrease in TC activity. In contrast, wind shear as a physical quantity has an indirectly proportional relationship with a favorable environment for TC formation (DeMaria, 1996; Gray, 1968). Therefore, a decrease of normalized wind shear in this study indicates strengthening of future physical wind shear which is a less favorable environment for TC formation. In a similar assessment, Camargo (2013) reached a similar conclusion for the SPO using selected model outputs from the CMIP5 ensemble of future climate projections. This is an example of how the statistical downscaling approach further enhances GCM output when assessing TC activity at a regional scale. Because GCMs struggle to reproduce TCs and hence could not be relied on to realistically provide climate information, TC activity in the GCMs is determined by applying individual large–scale environmental factors (Camargo, 2013).

5.11 Uncertainties in the future climate

There are number of uncertainties related with the future derived TC climatology in this study. The first source of uncertainty is the inability of GCMs to credibly resolve details of regional and local climate. To illustrate, the resolution of GCMs is too coarse to represent smaller scale processes such as interaction of circulation with small scale topography features, thunderstorms, atmosphere–ocean coupling, the spectrum of ENSO variability, spatial distribution of precipitation over tropical oceans and the cloud microphysics processes (Australian Bureau of Meteorology & CSIRO, 2011b; Collins & Bitz, 2006; Randall et al., 2007). These unrepresented and misrepresented processes are essential in the development of cyclone formation and play vital roles in sustaining and the spatial distribution of TC system (Gray, 1998; Gray, 1975). According to Benestad et al., (2007), a contributing factor towards unrealistic representation of regional details by climate models is attributed to incomplete understanding of the climate system (e.g. detailed understanding of the mechanisms that control ENSO across the equatorial pacific). Furthermore, selecting a specific CCSM simulation in the current study is among many possible global climate projections that could have chosen for the South Pacific domain. A list of 18 climate simulations were recognized and recorded in the PCCSP report (Australian Bureau of Meteorology & CSIRO, 2011b; Australian Bureau of Meteorology & CSIRO, 2011a).

Based on the improved skill after applying genesis indices over the hotspot region, there is also a chance of missing any plausible future events and processes. Statistical downscaling approach relies on long–term historical data (Benestad et al., 2007) and in this study it
accounts only for the period 1981 to 2010. The key theoretical weakness is the assumption that the statistical relationship between the NCEP/NCAR reanalysis climate and observed TC historical data will be the same under various forcing conditions in the future for the South Pacific climate (Australian Bureau of Meteorology & CSIRO, 2011a; Benestad et al., 2007; Meehl et al., 2007; Wilby et al., 2004). To illustrate, naturally occurring future climate forcings such as massive volcanic eruptions (Wilby et al., 2004) may contradict to the findings in this study. Additionally, selecting GP and CGI to statistically downscale future SP climate is a source of uncertainty given that they have already shown low skills in predicting observed TC activity (Figures 23, 24 and 25). It is probably because of error in the formation of the indices with South Pacific meteorology but, using a new developed index or a relevant proxy with high significant skill to assess TC activity is among other alternatives in addressing this error. Clearly, there are many uncertainties in the future climate projection itself and the application of a moderate correlation only adds to that uncertainty.

However, this study is highlighting the pragmatism of potential TC genesis indices in the South Pacific. While sources of uncertainty are recognized in this study it is important to acknowledge two significant points. First, the degree to which GP and CGI are applicable in the recent climate (NCEP/NCAR reanalysis) hence they can be used to make credible and useful projections in the region. Second, projection presented is only a single estimate and represents one of the possible future scenarios. In summary, further research is required to fully understand TC behaviour in the South Pacific.
CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

The main findings and recommendations from this study are summarised below under four subsections; climatology, verification of existing TC indices in recent climate, statistical downscaling of future climate, and recommendations.

Climatology

Analysis of genesis location and TC tracks indicates that the majority of observed TCs were recorded in the western part of the equatorial Pacific during the period 1981–2010. Spatial distribution is sensitive to the extreme phases of the El Niño–Southern Oscillation, as documented in the literature and as expected because cyclogenesis is enhanced by warmer sea surface temperatures. As indicated by the Oceanic Niño Index, during El Niño events, when the warmest SSTs are in the eastern Pacific, more TCs were observed toward the east side of the SP basin. Accordingly, during La Niña events when the warmest SSTs were in the western Pacific, more TCs were observed toward the west side of the SP basin. Considering the timescales 1981–1990, 1991–2000, and 2001–2010, the number of observed TCs that entered the SP basin has decreased, and the lowest number of TCs in the SPO occurred during the most recent decade (2001–2010) of the 1981–2010 study period. The highest number of TCs occurred in 1993–1994 and 1997–1998. There is no trend in Category 1–3 tropical cyclones, while the number of most intense TCs has increased substantially.

Verification of TC genesis indices in recent climate

Application of genesis indices to NCEP/NCAR reanalysis data does not explain the annual frequency of observed TC activity well; therefore it is challenging to develop an improved index for the SP basin based on the technique pioneered by Gray (1979). Genesis Potential Index and Cyclone Genesis Index have improved skill only when they are applied over a subregion of the basin, referred to as the Main Development Region. A curve–fitting exercise showed that the Cyclone Genesis Index has higher skill than the Genesis Potential Index because it used wind shear and potential intensity only. The Genesis Potential Index added two more factors, absolute vorticity and relative humidity, and this reduced its skill relative to the Cyclone Genesis Index. Individual predictors showed different contributions: wind shear contributes more than the others, while potential intensity and relative humidity both have very low skill for explaining observed TC activity.
Statistical downscaling of future climate

By downscaling CCSM (A2) future output, Genesis Potential Index predicts a decrease in TC activity by 2090 and Cyclone Genesis Index predicts a small decrease in favourable environment for TC activity during the same period. Although different, these predictions both generally agree with predictions from previous studies, so they represent progress toward a consensus. Based on the ability of the genesis indices to predict past climate, fair confidence can be placed in their ability to make future predictions. Finally, the individual predictors also indicated that the environment for TC activity would be less favourable except for wind shear which is expected to decrease by 20\textsuperscript{1st} century in a warmer climate.

Recommendations

Based on the assessment and analysis in this study, the following recommendations are made for future work and use of these results by policy makers:

1. Future research is needed to further develop a specific TC genesis index for the SP basin and understand the physical mechanisms to improve TC assessment (current and future) in the region. Such research could study the use of island radiosonde data, the approach of Tropical Cyclone Heat Potential (TCHP) (Wada & Usui, 2007), or applications of the tropical cyclone activity index (CAI) (Haig et al., 2014).

2. Because the NCEP/NCAR reanalysis dataset may not represent SPO climate very well, future studies of the same nature should consider other reanalysis datasets (e.g., ECMWF) to assess how well they can represent TC climatology in the SP basin. Also, using multiple reanalysis datasets will allow researchers to explore uncertainty in the results.

3. Conclusions about future climate for the PICs in this study do not provide definite information about which TC characteristics (e.g., intensity, lifetime, distribution, or frequency) are decreasing, but only that the favourable environment for TCs is likely to decrease. This limitation in statistical downscaling suggests two important considerations for future work. First, dynamical downscaling is highly recommended. Second, policy makers should continue developing national and regional plans to strengthen community resilience against the impacts of TC activity. To acquire an idea of uncertainty associated with climate projection and emission scenarios, the
downscaling approach should be applied to many scenarios and climate models (e.g., CMIP5 runs). By testing the ability of retrospective runs of these models against historical observations, researchers can then determine if any of these models has a more accurate representation of the TC climate in the South Pacific.
REFERENCES


WMO. 2011. Regional Specialized Meteorological Centres (RSMCs) and Tropical Cyclone Warning Centres (TCWCs). http://www.wmo.int/pages/prog/www/tcp/Advisories-RSMCs.html.


APPENDIX

This section provides additional information including definitions of terms and other relevant concepts that are important in the study.

A1. Terms and definitions

Absolute vorticity

Vorticity is the measure of the rotation of a flow and is calculated as a cross product of the vector wind. Absolute vorticity is the total motion of observed atmospheric winds and the Earth’s rotation. It is one of the favorable conditions to TC formation.

Climate change

Changes in the state of the climate that can be identified by statistical tests or changes in mean or the variability of its properties. These changes persist for longer periods of time, say decades or longer.

Climate models

Mathematical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties.

Climate variability

The variations in the mean state and other statistics such as (standard deviations, occurrence of extremes) of climate on all spatial and temporal scales beyond that of individual weather events. Variations can be due to (1) natural internal processes within the climate system, or (2) to variations in natural or anthropogenic external forcing. The ENSO cycle is a good example of sources in climate variability across the equatorial Pacific.

Climate

Description of atmosphere over relatively long period of time in a particular area.

CMIP3/CMIP5

Phases 3&5 of the Coupled Model Intercomparison Project (CMIP3 and CMIP5), coordinating and archiving climate model simulations based on shared model inputs by modeling
groups around the world. CMIP3 multi-model dataset includes projections using SRES scenarios. The CMIP5 dataset includes projection using the Representative Concentration Pathways.

**Curve fitting exercise**  
A method used in this study to compare predictions by tropical cyclone genesis indices with individual variables in NCEP/NCAR reanalysis dataset with interannual variations of observed TC activity in the SP basin. It is fitting the data of the two curves to assess the ‘goodness’ of the fit and the strength of the relationship.

**East trade winds**  
Refers to east to south-easterly winds which persistently affect tropical and sub-tropical regions, including northern region of Australia.

**Genesis Potential Index**  
An empirical relationship or the tropical cyclone index that was developed by Emanuel and Nolan (2004). It consists of potential intensity, relative humidity, vorticity, and wind shear.

**Global Scale**  
Term often used to describe global level or accounts for entire planet.

**ITCZ**  
The Intertropical Convergence Zone is a region where the northeast and southeast wind meets. It is marked by low pressure, rising motion, and thunderstorms, which occur with strong surface heating. Its latitudinal position shifts in response to the solar maximum and heating response of the surface. At times it is co-located with low pressure region known as ‘Equatorial Trough’.

**Kelvin waves**  
Eastward propagating waves at the equator with negligible velocity component and Gaussian latitudinal structure in zone velocity, geopotential, and temperature, symmetric about the equator. It causes variations in the depth of the oceanic thermohaline, the different aspect of the ocean circulation in
which salinity and temperature differences drive a large current.

**MJO**  
Madden Julian Oscillation is a band of low atmospheric pressure originating off the east coast of central Africa travelling eastward the Indian Ocean and northern Australia every 30 to 60 days. The state of MJO can help establish the timing of rainfall across much of the tropical Australia. In summer, the MJO can intensify and even establish the monsoon as well as help trigger tropical cyclones.

**MRG**  
The Mixed Rossby-gravity is a divergent Rossby wave, resulting from conservation of potential vorticity and buoyancy forcing. Their meridional velocity is symmetric about the equator and propagates westward in 3-6 day period.

**Model output**  
Simulated data from Global Climate Models under different emission scenarios.

**Model Resolution**  
How large the grid cells in a model are and the sizes of the time steps used in the model.

**Pacific Island Countries**  
All the Island and atoll countries of the SPO. It includes PNG, Solomon Islands, Vanuatu, Samoa, Tonga, Fiji, Tahiti, Tuvalu and etc.

**Potential intensity**  
The theoretical estimate of the maximum intensity of a tropical cyclone. It accounts for dissipative heating, SST, SLP, atmospheric and temperature profile at various levels.

**Prediction**  
Refers to the prediction or simulation by tropical cyclone genesis Indices and individual predictor.

**R squared**  
Statistical measure of how close TC observations are to prediction by the TC genesis indices.

**Regional scale**  
At local or national level, or a portion of global scale.
**Relative humidity**

Measure of the actual amount of water vapor in the air compared to the actual amount of water that can exist in that air at its current temperature. It is usually expressed in percentage and the current study uses humidity at 850 hPa level as one indicator of whether the large scale environment is favorable for TC formation.

**Rossby waves**

A series of troughs and ridges on quasi-horizontal surfaces in the major belt of upper tropospheric westerlies that result from conservation of potential vorticity. Normally, they always travel from east to west. However, if they are embedded in westerlies that have greater velocity than their propagation speed, the wave pattern will travel to the east in the earth-relative coordinates. They have major impact on the large-scale atmosphere and ocean circulation and therefore on weather and climate. They are also referred to as planetary waves.

**SST**

Sea surface temperature refers to warm ocean water with at least 26.5°C through sufficient depth of around 50 meters as defined by Gray (1975).

**SPCZ**

The South Pacific Convergence Zone is the most large-scale and persistent rain band in the southern hemisphere, extending northwest to southeast from the western Pacific warm pool and southeast towards French Polynesia. Changes in its position have significant impact on TC development in the SPO.

**Statistical downscaling**

In this study, it refers to the use of an empirical relationship (e.g., tropical cyclone genesis index) to identify TC activity in future climate data.

**Sustained wind speed**

TC intensity is defined by the maximum wind speed over land or water. This is also referred to as maximum sustained wind and will typically be experienced around an intense tropical cyclone.
**TC basin**

Definition of the domain of tropical cyclone basin by the WMO for the SP basin. The SP basin encloses the domain 0–30°S, 160°E–120W.

**Ten minutes averaging**

The observed mean wind speed over a 10-minute period of time. 10-minute average is the WMO standard measurement.

**Tropical cyclone**

The term refers to non-frontal synoptic scale low-pressure system over tropical and sub-tropical waters with organized convection and definite cyclonic surface wind circulation. It is used for systems of 34 knots and above. Different locations use the terms hurricanes, typhoon, and severe tropical cyclone.

**Weather**

What conditions of the atmosphere over a short period of time (e.g., rainfall today morning).

**Wind shear**

The magnitude of wind change with height. For TCs, typically this quantity is measured between the surface and the upper troposphere. Large values of wind shear destroy the incipient and formation of TC activity. In contrast, weak wind shear is a favorable environment for TC formation and development.

### A2. Counting and shift in TC categories in the SPO

Trend analysis and shift of TC categories on decadal timescale are given as a separate analysis in this report. TC categories are according to the Australian TC Intensity Scale.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>47</td>
<td>108</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>79</td>
<td>82</td>
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<td>3</td>
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<td>4</td>
<td>21</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>
Table A2a. Table showing the total number of TC categories per decade for the period 1981-2010 in the SPO.

Counting of TC categories was made by using NCL programming tool per decade (Table A2a). Assessment of individual TC categories over each decade was made to determine if there have been any clear trends in observed TC activity over the entire period of study (30 years period).

A3. The Australian Tropical Cyclone intensity Scale

<table>
<thead>
<tr>
<th>Category (cat)</th>
<th>10 minute wind speed (knots)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (tropical cyclone)</td>
<td>34-47</td>
<td>Damaging winds</td>
</tr>
<tr>
<td>2 (tropical cyclone)</td>
<td>48-63</td>
<td>Destructive winds</td>
</tr>
<tr>
<td>3 (severe tropical cyclone)</td>
<td>64-85</td>
<td>Very destructive winds</td>
</tr>
<tr>
<td>4 (severe tropical cyclone)</td>
<td>86-110</td>
<td>Very destructive winds</td>
</tr>
<tr>
<td>5 (severe tropical cyclone)</td>
<td>over 110</td>
<td>Very destructive winds</td>
</tr>
</tbody>
</table>

Table A3. Table showing TC categories according to the Australian TC intensity Scale (Fiji Meteorological Service, 2014).