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Feb2005
ANALYSIS OF TROPICAL CYCLONE TRACK SINUOSITY IN THE SOUTH PACIFIC REGION USING ARCGIS

by

Philip Malsale

A thesis submitted for the fulfillment of the requirements for the degree of
Master in Environmental Science

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School of Earth and Environmental Science
Faculty of Science, Technology and Environment
The University of the South Pacific

November, 2011
DECLARATION

Statement by Author

I, Philip Malsale, 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.

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Statement by Supervisor

This research in this thesis was performed under my supervision and to my knowledge is the sole work of Mr. Philip Malsale.

Signature: [Signature]  Date: 31 Jan 2012

Name: William Aalbersberg

Designation: Professor
DEDICATION

This research is dedicated to my beloved family, my wife Rose Aimie and children; Renay Merione, Philycia Lekita, Philip Junior, Jasmine Vale and Damien Geoffrey. I value your love and support that see me through this work. Many thanks and finally more time to spend at home.

To my wonderful parents Oted Malsale and Ruth Lekita and Uncle Richard Ilo and entire families, you have been instrumental in directing and investing in me. You are determine to provide the best for our family. Many thanks and may God grant more years to your lives to spend with us.
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Most of the references used in this research were provided by Dr. Suzana J. Camargo whom I am truly grateful for her contributions.

To others whom are not mentioned, your contribution has not gone unnoticed.
ABSTRACT

Tropical cyclones (TCs) are the most destructive natural disaster in the South Pacific region. Inhabitants whose livelihoods depend on agriculture and marine resources are vulnerable to such events which can pose a threat to their fragile living environment. Patterns of TCs depend on many migratory climate drivers such as the South Pacific Convergence Zone (SPCZ), the Intertropical Convergence Zone (ITCZ), Subtropical high pressure cells and large scale circulations such as the El Niño Southern Oscillation (ENSO) and Walker circulation. These drivers in many ways present the ideal climate conditions that provide the South Pacific region with the climate it is known for. Negative impacts of TC such as flooding, storm surge and fierce winds can cause damages to the social and economic livelihoods of Pacific Island people. These impacts vary depending on the level of vulnerability of each island nation and rely on economic, social status, geographical location and size.

Gathering additional information apart from TC frequency and intensity can assist in reducing related impacts and has long term benefits compared to providing aid to tropical cyclone impacted communities. Therefore, a TC database of best track was constructed with the introduction of a new metric for tropical cyclone track shape known as sinuosity values. This analysis for the South Pacific region specifically covered the Fiji Meteorological Services (FMS) Area of Responsibility (AoR) extending from the equator to latitude 25° S and longitude 160° E to 120° W from 1969-70 to 2007-08. This study has developed four sinuosity categories of tracks namely straight, slightly curved, highly curved and heavily sinuous. Analysis showed sixty eight percent of these tracks occurred in the western end of dateline and thirty two percent to the eastern end. A majority of them occurred during the months of January to February. Over the 39 year period, tracks in sinuosity category one and two peaked during 1970s and 1980s but show a declining trend thereafter while the two higher sinuous categories have increased trend in the last decade compared to the previous three decades. The same patterns were found using two case studies of the Vanuatu Area of Responsibility (AoR) and the case study of period 1990 to 2000 for FMS AoR.
The findings of this study concluded that sinuosity values have weak correlation with ENSO indices such as the Southern Oscillation Index (SOI), Sea surface Temperature (SST – Niño 3.4) and the Coupled ENSO Index (CEI), where the latter proves to have a highest $r^2$ value of 0.019. During El Niño years, track sinuosity values increase while during La Niña events, less sinuous tracks occur with a higher degree of dependency on the coupling of the SOI and SST. Basically, less sinuous TCs have less longevity but higher magnitude than more sinuous tracks.

Moreover, the findings concluded that track sinuosity is a significant component influencing the vulnerability of Pacific Island nations to cyclone hazards. Island nations will continue to experience irregular tropical cyclone characteristics.
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ABV  Australian Business Volunteers
ACE  Accumulated Cyclone Energy
ADB  Asian Development Bank
AoR  Area of Responsibility
AVN  Operational Aviation Model
BoM  Bureau of Meteorology (Australia)
CEI  Coupled ENSO Index
CH  Continental High
EEZ  Exclusive Economic Zone
ENSO  El Niño Southern Oscillation
ESCAP United Nations Economic and Social Commission for Asia and the Pacific
FMS  Fiji Meteorological Service
GIS  Geographic Information System
GTS  Global Telecommunication System
IPO  Interdecadal Pacific Oscillation
ITCZ  Intertropical Convergence Zone
JTCW  Joint Typhoon Warning Centre
MEI  Multivariate ENSO Index
MSLP  Mean Sea Level Pressure
NMS  National Meteorological Services
NOAA  National Oceanic and Atmospheric Administration
OCI  Operational Oceanic Index
PCCSP The Pacific Climate Change Science Program
PDO  Pacific Decadal Oscillation
PNG  Papua New Guinea
QBO  Quasi-Biennial Oscillation
RSMC  Regional Specialized Meteorological Centre
SH  Pacific subtropical high
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<td>Sea level Pressure</td>
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<td>SPCZ</td>
<td>South Pacific Convergence Zone</td>
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<td>SPSS</td>
<td>Special Package for Social Science</td>
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<td>SSTA</td>
<td>Sea Surface Temperature Anomaly</td>
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<td>SST</td>
<td>Sea Surface Temperature</td>
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<td>STD</td>
<td>Standard Deviation</td>
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<td>SWP</td>
<td>Southwest Pacific</td>
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<td>TC</td>
<td>Tropical Cyclone</td>
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<tr>
<td>TCWC</td>
<td>Tropical Cyclone Warning Centre</td>
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<td>USP</td>
<td>University of the South Pacific</td>
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<td>VMS</td>
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Tropical cyclones (TCs) are the most damaging natural disaster in tropical regions and the South Pacific region is not an exception. It has long been observed that the movement of tropical cyclones with their destructive potential in this region can be described, generally, from a direction of west to east.

There have been many studies focusing mainly on the intensity and frequency of tropical cyclones but not on the characteristics of their tracks. In all cyclogenesis regions, cyclone movements are not linear. Different tropical cyclone tracks have different shapes and lengths which are important characteristics. Information and research on tropical cyclone tracks has not been widely performed in this region.

This research paper aims to provide knowledge that will assist further research into this area to better understand this natural phenomenon. Furthermore, the characteristics of tracks can be utilized by National Meteorological Services (NMS) across the region in seasonal tropical cyclone bulletins alongside frequency and intensity forecasts to mitigate loss and damages.

This is important to the South Pacific region which consists mainly of islands surrounded by open ocean, a favorable condition for tropical cyclone formation. The vastness of the ocean in this region with its interaction with the atmosphere during TC events coupled with other factors makes it difficult for weather prediction models to accurately forecast the tropical cyclone track. Because of the negative impacts this will cause, coupled with the economic dependency of these islands on agriculture and tourism, there is a great need to better understand the movement of tropical cyclones.
1.2 Conceptual framework

It has been shown by researches that the El Niño Southern Oscillation (ENSO) has an effect on the climate system which also impacts the tropical cyclone characteristics around the globe. Research done by Landsea (2000) reviewed how tropical cyclone frequency, intensity and areas of occurrence were altered by the different phases of ENSO due to factors such as sea surface temperature and changes in environmental conditions surrounding them. These factors will be briefly mentioned but the main focus of this study will be on:

- Tropical cyclone track sinuosity values during the past 39 years.
- Naming of four different sinuosity categories.
- The spatial and temporal distribution of sinuosity categories over the Fiji Meteorological Services (FMS) Area of Responsibility (AoR) with case studies for Vanuatu Meteorological Services (VMS) AoR and TCs happening during 1990 to 2000 period
- The correlation between the sinuosity values and ENSO indices such as Coupled ENSO Index (CEI), Sea Surface Temperatures (SST) and Southern Oscillation Index (SOI) and other elements of TC tracks.

The sinuosity value of a track provides the main focus of this research. The information is significant beyond a scientific perceptive. The sinuosity values can be representative of the destructiveness of a tropical cyclone event and this has importance and relevance to the people in the South Pacific. The magnitude of damage by a cyclone with a high sinuosity value with gale force winds can be of the same magnitude to a hurricane force cyclone with a low sinuosity value travelling at a much higher speed.

The inclusion of track sinuosity in cyclone forecast bulletins based on ENSO phase can provide additional information not only for the weather forecasters but also knowledge for the general public to utilize for planning purposes. The inclusion of sinuosity values in tropical cyclone advisories may not only indicate the potential magnitude of damage
in a tropical cyclone event, but it also relates to the longevity or lifespan of a tropical cyclone. It is believed and has been part of traditional knowledge that for communities experiencing longer tropical cyclone systems, there is a greater chance of having a higher sinuosity value leading to an indication that the longer it survives (taking loops and turns), the more associated damage it causes.

These types of valued traditional knowledge of weather-related events being passed down by generations have scientific elements attached to them. Older generations from my home island in Vanuatu utilize this knowledge to predict cyclone tracks or movement despite the lack of communication of official warnings from the National Meteorological Service (NMS) to rural communities.

I am always enthusiastic to listen to my father (Oted Malsale) with other village elders in Uripiv Island (an island in Central Malekula, Vanuatu) explaining the possible track of a tropical cyclone during an event with reference to our island. The villagers, despite having very limited or no scientific knowledge of the factors controlling TC movements, are able to make their analysis and have some degree of accuracy that can be matched with the official prediction from Vanuatu NMS. This is what is usually mentioned when wind is coming from a certain direction with reference to Uripiv Island:

<table>
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<th>Local name (Uripiv Island dialect)</th>
<th>Prediction of cyclone direction</th>
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<tr>
<td>Northwesterly winds</td>
<td>Obuwere</td>
<td>Cyclone is approaching from north</td>
</tr>
<tr>
<td>North/Northeasterly</td>
<td>Dolu buwere/Dolu</td>
<td>The cyclone is located somewhere north but on the eastern side of the island.</td>
</tr>
<tr>
<td>Westerly/Southwesterly</td>
<td>Naru/Naru Daunau</td>
<td>Cyclone located down south and further moving away.</td>
</tr>
<tr>
<td>Easterly</td>
<td>Merié/Ling ewel ngalu</td>
<td>Cyclone located to the east of the island but still north</td>
</tr>
<tr>
<td>Southeasterly</td>
<td>Narosiw</td>
<td>The system is further down to the southeast of the country and moving away</td>
</tr>
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<td>--------------</td>
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</table>

Table: 1.1. Local names for wind direction in Uripiv dialect use in tropical cyclone forecasting

Though having very limited knowledge on how the environmental conditions influence the movement of tropical cyclones, these explanations are fairly accurate regarding the wind directions from the cyclone center and people in Vanuatu have lived with this knowledge for generations. The only limitation to this knowledge is that there is no mention of whether cyclones will loop, turn or migrate in a straight path which is essential information.

The different characteristics of track movements such as loops, turns and straight track of TC events influence their track sinuosity. These characteristics are associated with factors that may give insights into ways of devising methods that may reduce tropical cyclone track forecast errors. Some of the factors are on and above the earth’s surface such as:

- Effect of an island’s terrain
- Upper level environmental conditions (environmental flow)

It is the main objective of this paper that historical, temporal and spatial tropical cyclone track sinuosity will be assessed to provide an important component of tropical cyclone track characteristics to be included in seasonal TC advisories for the NMS.

1.3 Thesis organization

This thesis paper consists of seven chapters. The first chapter provides an introduction to the research followed by chapter two which presents information on the research setting. Chapter three outlines the methodology used especially on how the data are collected and analyzed. A review and description of the climatology of tropical cyclones in the
South Pacific with related literature on this research from other parts of the world makes up chapter four. Analysis of data and results will be discussed in chapter five where the focus will be on the spatial and temporal sinuosity pattern and correlation analysis. Chapter six will discuss the significance of the results in the previous chapter and compare them to other related studies in similar field. Chapter seven will summarize the thesis and reflect on the main objectives of this study and provide some recommendations for future research and how to improve shortcomings encountered during this study.
CHAPTER: 2. BACKGROUND OF STUDY AREA

2.1 South Pacific Region

There are six cyclogenesis regions in the world where TC studies are based and with related tropical cyclone research gaps that need to be addressed by meteorologists or people who are keen to contribute not only to tropical cyclone issues but environmental issues at large. This research focus on the South Pacific region (figure 2.1), a region where researchers have not shown much interest due to poor data collection and data inconsistencies until very recently. The South Pacific region is located in an enormous expanse of water, stretching across 20 million square kilometers with thousands of islands belonging to more than fifteen developing island nations, states and territories (Terry, 2007). From west to east these include Solomon Islands, New Caledonia, Vanuatu, Nauru, Kiribati, Tuvalu, Fiji, Wallis and Futuna, Tonga, Tokelau, Samoa, American Samoa, Niue, Cook Islands and French Polynesia as shown in figure 2.1. According to ESCAP (2010), all are members of the Alliance of Small Island Developing States (AOSIS) except for the French territories of New Caledonia and French Polynesia. Kiribati, Samoa, Solomon Islands, Tuvalu and Vanuatu are also Least Developed Countries (LDCs). All these countries are members of the Pacific Forum which has a vision that the region should be and will be a region of peace, harmony, security and economic prosperity, so that all of its people can lead free and worthwhile lives.

A few of the countries in the region are governed by other countries in the world like New Zealand and France. Regardless of these political boundaries, natural phenomena like tropical cyclones can affect these island countries. A majority of them, especially those below the equator, fall under the responsibility of the Fiji Meteorological Services (FMS) for recording and archiving tropical cyclone activity while some National Meteorological Services in the region also have their own Tropical Cyclone Warning Centre (TCWC) but all are under the directive and responsibility of the Regional Specialize Meteorological Centre (RSMC V) in Nadi, Fiji.
Before FMS became established in 1975, New Zealand was responsible for tropical cyclone naming and monitoring in the region by personnel stationed in Fiji. In 1997, RSMC was established in Fiji by the World Meteorological Organization (WMO) which authorized the center to be one of the three RSMCs in the region responsible for the monitoring and naming of tropical cyclones. However, there are a few TCs named by Meteo France because of their formation proximity to New Caledonia. Despite these few cases, FMS still have the sole responsibility performing these roles in the South Pacific region.

Figure 2.1. The South Pacific islands. The area of responsibility of the RSMC-Nadi in Fiji (grey box), and the island nations and territories across the tropical South Pacific (Source: Terry, 2010).

The FMS area of responsibility (AoR) extends from the equator to latitude 25° S and from longitude 160° E to 120° W (figure 2.1). It provides weather forecasts, issuing tropical cyclone warnings and other meteorological information to countries within its area of responsibility for the safety of all communities including marine and aviation users (Terry, 2007).
The Nadi RSMC AoR, especially the latitudinal boundaries, is an ideal location to study the behavior of tropical cyclones in this region. The latitudinal boundaries of this research coincide with the findings that Southern Hemisphere tropical cyclones rarely occur north of 10° S and south of 25° S. Tropical cyclones do continue to higher latitudes and even reach New Zealand, but as they move further south over the cooler water they lose their warm cores and cease to be true tropical cyclones or become ex-tropical cyclones. The longitudinal area covers all South Pacific countries. Despite the large geographical spread of this research area, tropical cyclone data are archived and provided from two countries (Fiji and New Zealand) in this region and each database can provide data when there are missing data from certain TC events.

2.2 Population

The Melanesian countries, namely Fiji, Papua New Guinea (PNG), New Caledonia, Solomon Islands and Vanuatu, are the biggest group of islands in the region in terms of landmass, population and languages compared to other groups (Polynesian and Micronesian) that make up the South Pacific islands countries (table 2.1). The area covered by the Melanesian countries experiences the greatest number of tropical cyclone. In the whole of the South Pacific region, there are about ten (10) million people excluding Australia and New Zealand. With this population size, youths between 15 to 24 years of age make up 20% of the countries’ population and in some cases half of the population (ESCAP, 2010).

This population size creates a number of pressing environmental, economic and social challenges in these countries. Many countries are struggling to find solutions to these, and have encouraged the South Pacific Forum to find solutions outlined in the so-called “Pacific Plan”. These challenges include the disintegration of the family unit, the lack of educational and employment opportunities, the tension between culture and globalization, gender inequality, the rise in HIV cases, and adherence to good governance principles (ESCAP, 2010).
<table>
<thead>
<tr>
<th>Country</th>
<th>Land Area (km²)</th>
<th>EEZ Area (km²)</th>
<th>Population (estimated for mid-2009)</th>
<th>GDP/capita (USD)</th>
<th>GDP Growth Rate 2007 (estimated)</th>
<th>Human Development Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook Is</td>
<td>237</td>
<td>1,830,000</td>
<td>15,636</td>
<td>10,007</td>
<td>0.4</td>
<td>0.829</td>
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<tr>
<td>FSM</td>
<td>701</td>
<td>2,978,000</td>
<td>110,899</td>
<td>2,183</td>
<td>0.1</td>
<td>0.716</td>
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<tr>
<td>Fiji Is</td>
<td>18272</td>
<td>1,290,000</td>
<td>843,883</td>
<td>3,182</td>
<td>-3.9</td>
<td>0.718</td>
</tr>
<tr>
<td>Kiribati</td>
<td>811</td>
<td>3,550,000</td>
<td>98,989</td>
<td>656</td>
<td></td>
<td>0.597</td>
</tr>
<tr>
<td>Marshall Islands</td>
<td>181</td>
<td>2,131,000</td>
<td>54,065</td>
<td>2,851</td>
<td>2</td>
<td>0.708</td>
</tr>
<tr>
<td>Nauru</td>
<td>21</td>
<td>310,000</td>
<td>9,771</td>
<td>2,820</td>
<td>0.2</td>
<td>0.637</td>
</tr>
<tr>
<td>Niue</td>
<td>259</td>
<td>390,000</td>
<td>1,514</td>
<td>5,854</td>
<td>5.5</td>
<td>0.821</td>
</tr>
<tr>
<td>Palau</td>
<td>444</td>
<td>616,000</td>
<td>20,397</td>
<td>8,423</td>
<td>6.2</td>
<td>0.81</td>
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<tr>
<td>PNG</td>
<td>462840</td>
<td>3,120,000</td>
<td>6,609,745</td>
<td>1,062</td>
<td>6.2</td>
<td>0.437</td>
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<tr>
<td>Solomon Islands</td>
<td>2935</td>
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<td>182,578</td>
<td>2,860</td>
<td>4.7</td>
<td>0.762</td>
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<tr>
<td>Tonga</td>
<td>14874</td>
<td>70,326</td>
<td>1,155,000</td>
<td>392</td>
<td>16.2</td>
<td>0.489</td>
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<tr>
<td>Tuvalu</td>
<td>650</td>
<td>700,000</td>
<td>103,023</td>
<td>1,874</td>
<td>-3.5</td>
<td>0.737</td>
</tr>
<tr>
<td>Vanuatu</td>
<td>26</td>
<td>900,000</td>
<td>11,093</td>
<td>1,563</td>
<td>3</td>
<td>0.691</td>
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<td>Total</td>
<td>542,811</td>
<td>20,025,326</td>
<td>9,990,503</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1. Statistics of Pacific Island countries (Source: ESCAP, 2010).

2.3 Environment

The region of the South Pacific comprises islands with different sizes, age and origin which influence their capacity to adapt to changes. For example, those of small size can be entirely devastated by a natural disaster with the sustaining environment and livelihoods virtually destroyed. Therefore decades of development efforts can be eliminated in a few hours, as demonstrated by cyclone Heta in Niue in January 2004 and the earthquake and accompanying tsunami in Samoa in April 2007 (ESCAP, 2010). Such wide spread damage can have an impact on the diversity of the island nations especially the small atoll nations such as Tuvalu and Kiribati.

The larger and older countries in the region, generally, the Melanesian countries (PNG, Solomon Islands, New Caledonia, Vanuatu and Fiji) support both a greater diversity of
terrestrial ecosystems, and a greater diversity of plants and animals. They have similar features like the sea separating islands and the rugged interiors separating catchments and lowland habitats which can be barriers to the movement of many species, providing conditions that have favored relatively rapid sub speciation and speciation (ESCAP, 2010). Frequent disturbances due to the passage of tropical cyclones or volcanic activity have also had a major affect on the distribution and abundance of species, especially on smaller islands countries such as those in the Micronesian group.

The South Pacific region's flora is closely aligned with that of SE Asia and within neighboring group of islands. For example, 59% of palm genera from Vanuatu are shared with Fiji with a much lower proportion affiliated with palms in Solomon Islands. Similarly the fauna demonstrates close affinities with Solomon Islands. Internally there is a biogeographic divide with volcanic islands to small islands in Polynesia and Micronesian (ESCAP, 2010). In general the South Pacific region's biodiversity remains poorly known.

Despite a strong understanding of their environment, many Pacific Islanders often have little perception of increasing vulnerability, especially due to longer-term changes. People living on small islands generally understand their island, its characteristics and how to build resilience, yet do not have the adaptive capability or sufficient alternative options and resources to cope with significant environmental changes. Future implications are the likelihood of increased vulnerability with less understanding of current and potential risk. In recent years, much work has been undertaken by development partners to strengthen community resilience through disaster risk reduction by building on traditional knowledge and systems.

2.4 Politics

Politics in many of the countries takes place in a framework of a parliamentary representative democratic republic, whereby the Prime Minister is the head of government, and of a multi-party system (ESCAP, 2010). Executive power is exercised
by the government. However, there are a few countries (New Caledonia, Wallis and Futuna and Tahiti) in the region that are still colonies of France and also a few administered by New Zealand. Being relatively young democracies, most of the island nations face a wide range of development challenges which include governance and capacity development of public institutions in particular according to ESCAP (2010).

Legislative power is vested in both the government and parliament. The Judiciary is independent of the executive and the legislature. Forming coalition governments, however, has proved problematic at times, owing to differences between languages, for instance in Vanuatu, between the French and English speaking parties. In a country like Fiji, a race difference in a coalition government was a factor in the last three coups. Therefore it has been observed that the Melanesian countries are more politically unstable with large natural resources compared to the Polynesian and Micronesian countries that are more stable with less natural resource.

Parliament in most countries has elected members for a four year term in multi-seat constituencies. The president, in some countries like Vanuatu and Fiji, is elected for a five year term by the parliament. Parliament normally sits for a four year term unless dissolved by majority vote of a three-fourths quorum or a directive from the President on the advice of the Prime Minister. In these two countries, the national Council of Chiefs is elected by district councils of chiefs, advises the government on all matters concerning the culture, language and politics of the country.

2.5 Economy

The economic development of the island countries in the region is hindered by the dependence on relatively few export commodities that are highly vulnerable to natural disasters and remoteness to markets (ESCAP, 2010) and trade deficits have been on the rise due to declining exports and increasing imports. While commercial agriculture has been encouraged as a way forward, it thrives on fertile volcanic-based soils and the
increasing climate variability and lack of surface water storage does not help. Rainfall behavior in particular can be the key to success in the agricultural sector and quality of life of the people.

The climate is intimately interwoven with the affairs of everyday life, and there is hardly an aspect of human activities as dependent on the weather as agriculture. Agricultural production is for a large part still dependent on weather and climate despite the impressive advances in agricultural technology over time. More than ever, meteorological services are becoming more essential because of the challenges brought about by increasing climate variability, associated extreme events and climate change in general, all of which affect production and the socio-economic conditions, especially of developing countries. The countries in this region suffer from such challenges.

Agriculture and fisheries are the major components of these countries’ economy and are practiced in small scales either commercially or as subsistence. It supports directly the 70% of the population living in rural areas. As part of the Pacific Plan, countries in this region are implementing new development strategies and agriculture, marine and tourism are identified as a priority area for development (Asian Development Bank, 2003).

These new initiatives are driven by the maritime climate of this region where there are two (dry and wet) main seasons with annual average rainfall amount between 1500-2000 mm and mean temperatures of 28°C - 31°C. As irrigation is not practiced, traditional crop calendars were developed based on the usually distinct seasonal variations in rainfall. Large variabilities in climate consequently affect agricultural production and therefore the livelihood of people, especially in rural areas (Asian Development Bank, 2003). Tropical cyclones remain the major threat to agriculture in the country but droughts caused by ENSO have very devastating effects on agriculture and almost always cause large economic losses.

Tourism is an important sector in foreign exchange earnings for countries in this region. It has a wide range of products to showcase to the world with culture, sunshine, marine
life and sandy beaches form the bases of attractions. In countries like Cook Islands, Tahiti, Fiji and Vanuatu, this industry is a main foreign exchange earner but activity is centered in the main centers of these island countries like Nadi, Port Vila and Rarotonga (King, 1999). There is considerable potential for tourism growth, with adventure tourism and diving holidays supplementing resort tourism, and extending benefits out to the rural areas.
CHAPTER: 3. METHODOLOGY

This chapter describes the rescue and digitization of tropical cyclone (TC) data from the New Zealand tropical cyclone warning centre (TCWC) in Wellington and the Regional Specialized Meteorological Centre (RSMC) in Nadi, Fiji; the management of the digitized data in excel and homogenization of the data. The last part of this section provides an explanation on how TC data are used in ArcGIS for the benefit of this research. The study uses the same idea as Basher and Zheng (1994) to map the distribution of cyclone incidence but more emphasis will be based on the mapping of TC tracks to provide a spatial and temporal distribution of track sinuosity values based on their migration pattern during the tropical cyclone stage.

3.1 Database construction

The TC database was devised using a simple method of comparing the two data sets provided by TCWC in Wellington and RSMC in Nadi. Inspection of these data was done by comparing the data side by side to eliminate duplicate tracks. A complete excel database of tropical cyclone tracks including details prior to the system becoming a tropical cyclone has been created for this research. A schematic diagram of how the dataset is devised and data are analyzed is shown on the next page.
Figure 3.1. Schematic representation of how the TC dataset was devised and analyzed

3.1.1 Rescue of tropical cyclone data

The primary source of TC data provided for this study was in simple text format and was acquired from the Fiji Meteorological Services and the TCWC in Wellington, New Zealand. The collection of source data builds upon the excellent working relationship between the National Met Services (NMS) and the two centers for monitoring TCs in the South Pacific region especially over the FMS area of responsibility (AoR). The TC data were also cross-checked with TC reports from the NMS that were produced annually. The data were then transferred to excel format for sorting, verifying and validation using the two TC data sets. The New Zealand data comprised tropical cyclone data between the 1969-70 and 2005-06 seasons, while the Fiji data consisted of the 1992-93 to the 2007-08 TC seasons.
For some reasons FMS did not archive tropical cyclone coordinates from 1969-70 to 1992 while only tropical cyclone hard copy reports were available from 1977. New Zealand Meteorological Service has done a better job of archiving compared to FMS and probably because it is the first decade after FMS establishment therefore it was more focused mainly on operational issues with little time allocated for archival work and research. Archiving of tropical cyclones occurring with what is now FMS AoR is something New Zealand did prior to the establishment of RSMC in Nadi. The other reason why the archiving of tropical cyclones by FMS started around the 1995 cyclone season is because it (FMS) began tropical cyclone track verification in the early 1990s only when the TC analysis tool which is the Dvorak technique became available and currently employ the method as their primary TC intensity analysis tool (Velden et al, 2006). The full function of the RSMC became operational in June 1995 with TC reports submitted to WMO annually. New Zealand and FMS maintained a very close working relationship until the first Fiji coup in 1987 where cooperation between the two countries has been re-established. With the close working relationship between the two countries, there is sufficient and mostly complete tropical cyclone data available for the thirty nine year period 1969/70 to 2007/08 to use in this research.

3.2 Management of digitized tropical cyclone data in excel

The TC data for each centre were imported from the simple text format to an excel format for sorting, verifying and validating using the overall list of cyclones provided by both countries (Fiji and New Zealand). The list was also used to crosscheck with the excel database to ensure that all tropical cyclones occurring within the 1969/70 to 2007/08 seasons were included before transferring to the GIS database. The same process was done for both countries (New Zealand and Fiji) to ensure consistency in the tropical cyclone data.
The data extracted from the data sources had some typing errors and missing data such as wind speed, central pressure and position that are important to this research and any further studies. These problems were overcome by using complete data for any tropical cyclone from either FMS or New Zealand. In case of both data sources having accurate and identical data, the Fiji data were used while the NZ tropical cyclone data were eliminated unless they provided a better coverage of a particular tropical cyclone lifespan. Fiji data was given more priority especially within the region 160° E to 120° W and 0° to 25° S. This is because it is the area TCs are monitored under the Regional Specialized Meteorological Centre (RSMC) located in Nadi. From the two sets of tropical cyclone data, there are sixty (60) tropical cyclones starting at 35 knots or above. Out of the sixty (60), forty (40) started with wind speeds recorded starting above thirty five knots. The reason for this was that these tropical cyclones might have intensified so rapidly that data from the tropical depression stage were not recorded.

This issue was found in both datasets therefore more complete data (data beginning below 35 knots) from the FMS or New Zealand data sets were used depending on which one has the complete data set. Apart from this issue, there are others mentioned below where data from neither were used:

1. When data were not available at the tropical depression stage during an event.
2. When data did not include other variables such as pressure, wind and position.
3. When data sources did not have tropical cyclone data for a particular cyclone.

TC data used from the two tropical cyclone centers are winds greater than thirty four knots (gale force winds) from the beginning of an event. until the system becomes a post tropical depression or having wind speed of less than thirty five knots for a consecutive six hours period at the decaying stage of an event. Data for the following six hours was to make sure wind speeds were definitely decreasing.

During the sorting process, there were twelve (12) events that met tropical cyclone status (have wind speed 35 knots or over) but were not given any name. The reason is New
Zealand TCWC decided that a system deserved cyclone status while the RMSC in Nadi decided otherwise for some reasons with only the latter given the authority by WMO to name a cyclone within its area of responsibility (figure 2.1). It was also found that these systems (that have no name) appear to be more intense than the required windspeed threshold and have very short lifetimes. There were often other cases where the Joint Typhoon Warning Centre (JTWC) decided a system deserved cyclone status and Fiji and NZ did not. This is a good example that tropical cyclone monitoring in the Pacific is not perfect since various agencies have different definitions and standards.

Individual track data were not combined from Fiji and New Zealand because both use forecast data from different (reputable) meteorological centers and models. This is turned into a consensus forecast and may be adjusted slightly based on what the lead forecaster feels at the time and this becomes the Fiji and New Zealand forecast. There is no such rule that says Fiji and NZ must provide the same TC forecast. However considering Fiji has been given the authority by WMO for the region, the Fiji TC tracks details are used if TC data of the same event appear in both datasets. Likewise when monitoring a cyclone there may be different satellite data that each centre use conjunction with forecaster interpretations which may place the centre of the cyclone in a slightly different position using the Dvorak technique. Though the Dvorak technique has built experience and confidence in TC monitoring, the limitations become more apparent and local forecast centers have considered adding regional adjustments to ameliorate some of the deficiencies. These differences should be very small and it is worth noting that some of the applications are simple rules of thumb and not rigorously proven (Velden et al, 2006). This can affect the degree of accuracy for the position of tropical cyclone centre.

The problem of unnamed cyclones in the database is resolved by assigning numbers to tropical cyclones occurring within a year. For example in 1977, there were two unnamed cyclones. The first one is renamed 1977.1 and the second is 1977.2. The numbers assign after the year (1977) indicate the order of occurrence for this cyclone in that particular
year. The renaming intends to make a better and complete dataset where differentiating between tropical cyclones can be easy.

Transferring the tropical cyclone data from the simple text to the excel format saw a total of 102 tropical cyclones provided from the RSMC in Nadi (FMS) and 325 from TCWC Wellington for a total of 346. The total is different from the simple addition (102+325) which is 427. The reason is from 1992-03 to 2007-08 tropical cyclone seasons, the same tropical cyclones are listed on both datasets while a few are listed on only one dataset. Those that appeared in both datasets were entered once to the combine tropical cyclone database to avoid double counting. In other cases, there were some tropical cyclones that were only listed once in either the FMS or the TCWC in Wellington dataset are enter as one tropical cyclone to the combine tropical cyclone database.

Included in the two datasets are tropical cyclones originating in the Coral Sea that do not migrate to FMS AoR. A total of forty seven (47) tropical cyclones are found to fall into this category. They are included in the final list of tropical cyclones to provide a more complete tropical cyclone database despite the area of interest of this research. However these tropical cyclones will be excluded in the analysis part of this research. A final list of TCs was compiled including those occurring from the 1969-70 season to the 2007-08 season, in an excel format. This dataset also includes a complete list of tropical cyclones occurring in the area of research (160°E -120°W).

The final TC dataset contains tropical cyclone data entries at mostly 12 hour intervals from the 1969-70 season until 1985. After 1985 recording was done on a six hourly interval for each tropical cyclone. Each entry comprises name, date, time, location, central pressure, intensity of maximum winds based on the Beaufort scale (e.g., gale, storm and hurricane) and text comments. By the late 1960s, satellite imagery and information have ensured all storms are identified and that their intensities and tracks are well estimated since then, though there were some limitations such as limited Infra-Red (IR) imagery, no enhancement and animation capabilities (Velden et al, 2006). This
provides some confidence that data used in this research are of good quality. This analysis was restricted to a 39-yr database beginning with the 1969-70 cyclone season.

3.3 Digitization of tropical cyclone data in ArcGIS

The importation of this excel file into ArcGIS involves several procedures to enable the file format to be accepted in ArcGIS. The excel TC data are saved as a dbase format (.dbf), a file extension accepted in this software. Using the ArcCatalog, the latitude and longitudes in the excel files are given spatial reference by providing the coordinate system. In this study, the GCS_WGS_1984 was used and this provided the shape file to be used in ArcMap to display the point data (figure 3.2).

![Figure 3.2. Position of tropical cyclone data shown as a point](image)

However, in displaying the points in ArcMap, all the points were positioned at the both ends of the window indicating the referencing method used does not allow the points to be placed in the center of the window. Solving the problem involves changing all coordinates (y - coordinates) less than zero to continue from 180°. For instance the
longitude -179° is changed to 181°. This method enables the points to be placed in their appropriate places as shown in figure 3.2. The other method is changing the central median of the projection to 180 degrees which places Fiji at the center of the Map.

The points that are referred to as the TC observation times are then joined as polylines (figure 3.3) in ArcGIS which represent a track of a tropical cyclone event. These points are connected using the XTool Pro, an extension of ArcGIS software. The shape files of individual cyclone events were then merged to create a single shape file using the TC unique identification number and this file was used for analysis in ArcMap.

The main objective of this research was to allocate each TC track a sinuosity value. To achieve this, calculations were not done in ArcGIS but in the TC combination excel spreadsheet. Included in the spreadsheet are columns including the straight and curve distances which are calculated using the Haversine formula. This formula calculates the ratio between the curve and straight distance (curve/straight distance), which gives the sinuosity value which is the main focus of this research.
3.4 Calculating sinuosity value using Haversine formula

The Haversine formula is an equation used for the calculation of distance between two points. It assumes a spherical Earth and ignores ellipsoidal effects (Sarddar et al, 2010). It is important in navigation, giving great-circle distances between two points on a sphere from their longitudes and latitudes. This method is appropriate for this study as TCs do occur on a sphere and not a flat surface and capturing the dynamics in distance associated with a spherical surface is very important. The curve and straight track distances are calculated using the Haversine formula which is appropriate because it is only an approximation when applied to the Earth. For example, given a unit sphere, a "triangle" (Figure 3.4) on the surface of the sphere is defined by the great circles connecting three points u, v, and w on the sphere. If the lengths of these three sides are a (from u to v), b (from u to w), and c (from v to w), and the angle of the corner opposite c is C, then the law of haversines states:

(the law of haversines)

\[
\text{haversin} \ (c) = \text{haversin} \ (a-b) + \sin(a) \sin(b) \ \text{haversin}(c)
\]

Since this is a unit sphere, the lengths a, b, and c are radians multiplied by the radius of the sphere.

![Diagram showing a spherical triangle solved by the law of haversines](Image)

Figure 3.4. Spherical triangle solved by the law of haversines (Source: Sardar et al, 2010).
With the Haversine equation, the curve and straight distance values of cyclone tracks are calculated based on the wind speed of each TC. The distance values of the straight track are taken when the tropical cyclone wind speed starts at 35 knots until it first reaches the first 30 knots (which is below the TC wind speed threshold) during the weakening stage. In cases where a TC has wind speed at 35 knots at consecutive observations, then the sinuosity is taken starting from the first 35 knots to the first 30 knots during the weakening stage. This is to make sure that sinuosity values are for the tropical cyclone stage and not the depression or weakening stage of a system.

Bearing of tracks and other variables such as area covered by tracks are added as additional information calculated from the starting to the finishing point of a tropical cyclone system to provide an interesting sinuosity analysis. The mean global area covered by a TC event is calculated using the difference in latitude covered multiplied by the difference in longitude covered. The highest latitude is 25° south.

### 3.5 Tropical cyclone data homogeneity

Tropical cyclone data during the 1969-1970 to 2007-2008 cyclone seasons were collected and analysed during the satellite era using the Dvorak technique where procedures of identifying the final TC number are followed using the different pattern types a system has during its lifespan. Analysis techniques are not consistent throughout the period (after introduction of Dvorak method in 1973 (Velden et al., 2006) and there are small variations in some cyclogenesis regions especially on the timing of naming a system. The consistency in the analysis methods and the satellite imagery provides for accuracy especially for intensity (and TC category) and locating the system center. It also provides additional information on other variables such as wind speed and central pressure.

Therefore a new TC database was devised with all data from the Fiji Meteorological Services (FMS) and the TCWC in New Zealand. These data were then cross-checked with individual tropical cyclone reports that were available from each National
Meteorological Service (NMS) and once the data were verified and validated, they were then extracted to ArcGIS workable format.

3.6 **Use of tropical cyclone data in ArcGIS**

ArcGIS software is the main tool to analyze the spatial and temporal distribution of tracks. The main tools used in ArcGIS are ArcMap, ArcTool box and ArcCatalog. The analysis of the temporal distribution of TC track sinuosity was done using Excel and the Special Package for Social Science (SPSS) software.

3.7 **Coupled ENSO Index (CEI)**

This is a new index devised by Gergious (2005) to identify synchronous ocean (Niño 3.4 SST) and atmospheric (Southern Oscillation Index) anomalies associated with ENSO for the instrumental period (1871-2003). This research uses these data to establish relationships with the TC track sinuosity and will use the CEI values from 1969 to 2008 period. This new index is relevant to the scientific community as it provides a baseline for the calibration of proxy records to reconstruct both components of the ENSO system and it also facilitates systematic resolution of long term context of ENSO behavior. This index is appropriate for this research providing years where oceanic and atmospheric component of ENSO are in phase and how this influences TC track sinuosity.

Coupled ENSO Index = SST five months (smooth) -1 + SOI eleven months (smooth)

3.8 **Sea Surface Temperature (SST)**

The Sea Surface Temperature (SST) that represents the oceanic characteristics of ENSO was also used in this research obtained from the Niño 3.4 region (5° N - 5° S, 120° -170° W) and was also part of the data compiled by Gergis and Fowler (2005). It provides
higher mean temperatures than the Niño 3 region and its closeness to the west Pacific warm pool and main centers of ocean convection makes it ideal for this research. Very recently, this SST region was acknowledged by its selection as the geographical basis for National Oceanic and Atmospheric Administration (NOAA) operational Oceanic Index (ONI) (Elsey, 2004; Mc Phaden, 2004). Data from this region represent *in situ* measurements of SST variability, thus are considered to be the best available direct record of ENSO conditions (Gergious, 2005).

### 3.9 Southern Oscillation Index (SOI)

For the atmospheric characteristic of ENSO, this research uses the SOI sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soihtml). On the basis of the Troup (1965) method, this SOI time series (1871-1992) is the standardized anomaly of the mean sea level pressure difference between Tahiti and Darwin relative to the 1933-1992 base period. The SOI is represented in standard deviation units around zero, with significant positive/negative departures represent La Niña/El Niño conditions. The SOI is calculated as:

\[
\text{SOI} = \frac{10 \times (P_{\text{diff}} - P_{\text{diff}\text{av}})}{\text{SD}(P_{\text{diff}})}
\]

where:

- \(P_{\text{diff}}\) = (average Tahiti MSLP)-(average Darwin MSLP)
- \(P_{\text{diff}\text{av}}\) = long term average of \(P_{\text{diff}}\) for the month in question and
- \(\text{SD}(P_{\text{diff}})\) = long term standard deviations of \(P_{\text{diff}}\) for the month in question.
3.10 Regression and Correlation Analysis

The study also applies simple regression analysis as an explanatory tool to find out whether any relationships may exist between sinuosity as the predictant and predictors such as Coupled ENSO Index, Sea Surface Temperature (SST) especially over the Niño 3.4 region and the Southern Oscillation Index (SOI) using their monthly values. The regression analyses were done in Microsoft excel.

\[
\text{Sinuosity anomaly} = \frac{\text{sinuosity value of a tropical cyclone track} - \text{long term average}}{\text{Standard Deviation}}
\]
CHAPTER: 4. LITERATURE REVIEW

This chapter explores literatures on tropical cyclones, especially on track sinuosity studies around the globe. The first two sections will focus on FMS, RSMC and TC sinuosity. The majority of this section provides details on tropical cyclones; the definitions, their different classifications and outlining the cyclogenesis regions of the world (section 4.3). It also focus on the conditions favorable to tropical cyclone formation. Sections 4.7 to 4.11 explore the spatial distribution of tropical cyclones outlining reasons why tracks consist of different shapes, with particular reference to a case study in Taiwan. The last two sections will focus on the impacts of climate change on TC events.

4.1 RSMC and Fiji Meteorological Service

The World Meteorological Organization (WMO) nominated Fiji Meteorological Services (FMS) in 1995 as the Regional Specialized Meteorological Centre (RSMC) to oversee the collection, dissemination and archival of tropical cyclone information in the southwest Pacific Basin. Nadi became the latest to join the existing RSMC of Miami (USA), Tokyo (Japan), New Delhi (India), and La Reunion (France) to provide a combined global coverage of tropical cyclone warning and advisory services. Its main responsibility is to issue tropical cyclone advisories in a broad area south of the equator extending from the east coast of Australia to the French Polynesia (figure 4.1).

The National Meteorological Services (NMS) within the South Pacific region are also responsible for archiving meteorological data including tropical cyclone. However, the RSMC in Nadi archives all TC data oversees queries with regards to tropical cyclone operations in this region especially within the area from 160° E to 120° W and 0° to 25° S.
The FMS is also responsible for providing weather related information such as marine and aviation to smaller countries like Kiribati, Tuvalu, Niue, Tonga, Wallis and Futuna, Samoa, Tokelau and Cook Islands through the Global Telecommunication System (GTS) or email. These countries have little or no forecasting capabilities of their own and, in most cases, the information from Nadi is the only source of information available to them (Zschau, 2003).

Figure 4.1. Map of RSMCs and their coverage areas (Source: WMO Tropical Cyclone Programme – http://www.wmo.int/pages/prog/www/tcp/Advisories-RSMCs.html).

4.2 What is sinuosity

Sinuosity is a curvature method that has been widely used in research especially on coastline and river channels particularly on their spatial and temporal changes. However, very little work is done on tropical cyclone tracks sinuosity. More recently, Terry and Gienko (2011) specifically looked into this element as part of TC characteristics. This
research is part of the work published by Terry and Gienko (2011) and is the first done in the South Pacific region and probably first among few of its kind in the world, utilizing this method in the field of meteorology.

Tropical cyclone track sinuosity is the ratio of the distance along a digitized line to the length of the trend line connecting each end point (also called a route factor). In this study it is the ratio between the curve distances of a cyclone track divided by the straight distance taken from the starting to the finish point of that track. The sinuosity values derived are numbers to represent the ratio between the two distances previously mentioned and are not a distance measurement. This provides the idea that the more curvature a track has, the higher its sinuosity value compared to a less curved track that has a lower sinuosity value. Therefore all tracks with sinuosity values of one (1) are those that display almost straight track while others with more curvatures have values greater than one.

4.3 What is tropical cyclone

‘Tropical cyclones (also known as hurricanes or typhoons, depending on regions) occur most frequently in the six key regions of the world: in the northwestern Pacific, the tropical North Atlantic and the Caribbean, the northeastern Pacific, the southern Indian Ocean and the southwestern Pacific (figure 4.3). The northwestern Pacific has the greatest activity each year’ (Burroughs, 2003).

Of all natural disasters, tropical cyclones are the most expensive and deadliest around the world. For example, approximately three hundred thousand (300,000) death toll in the infamous Bangladesh cyclone of 1970 and the $26.5 billion (U.S.) in damages due to Hurricane Andrew in the southeast United States (Landsea, 2000). The same research identified hurricane property losses exceeding those due to earthquakes by a factor of four. This accounts for forty percent (40%) of all insured losses in the United States for the period 1984 to 1993. Understanding and predicting how both tropical cyclone
frequencies and intensities vary from year to year is a topic of great interest to, scientists, business and general public. In particular on how the spatial and temporal changes in tropical cyclone track pattern can influence the livelihood of people in the South Pacific Region.

The word “tropical cyclone” (figure 4.2) is subject to various interpretations with more emphasis on been a ‘generic term for a non-frontal synoptic scale low-pressure system that develops over tropical or sub-tropical waters with organized convection and a well-defined cyclonic surface wind circulation’ (Landsea, 2000 and Atkinson, 1971). The definition signifies nothing as to the intensity of the associated winds and weather or the thermal structure of the cyclone. However, the organized warm-core systems have the maximum wind speed near the surface and decrease in the intensity with height (Atkinson, 1971).

Terry (2007) describes the term ‘tropical cyclone system’ as an atmospheric heat engine where it originates from a state of thermodynamic disequilibrium that exists between the ocean and the atmosphere. Its energy source is primarily fuelled by evaporation and sensible heat flux from the sea in the presence of high winds and lowered surface pressure. These energy sources are obtained through condensation in convective clouds concentrated near the cyclone's "warm-core" center.
Figure 4.2. Satellite image of tropical cyclone Zoe on 27th December 2002, northeast of the main islands of Vanuatu. (Source: Terry, 2007).

The fierce winds and violence nature of tropical cyclone can be attributed to the enormous quantities of heat energy released by the condensation of water vapor contained in the rising tropical air masses. The energy released from a tropical cyclone is a result of ‘an attempt by the coupled ocean-atmosphere system to attain thermodynamic equilibrium’ (Terry, 2007). This is achieved by the transfer of heat from the warm sea to the cool atmosphere above through convection and condensation process.

4.4 Classification and definition of tropical disturbances

According to Atkinson (1971), there is no common international terminology for tropical disturbances or cyclones of various intensities. The terminology and definitions of tropical cyclone classes adopted by several countries illustrated the diversity of classification systems currently in use.
Tropical cyclones with maximum sustained surface winds of less than 18 ms\(^{-1}\) are called "tropical depressions". Once the tropical cyclone reaches winds of at least 18 ms\(^{-1}\), they are typically called "tropical storms" and assigned a name (Gray, 1975). Names are decided upon by the representatives from the RSMCs at the annual World Meteorological Organization regional meetings. If winds reach 33 ms\(^{-1}\), they are then called: "hurricanes" in the Atlantic Ocean, a "typhoon" in the Northwest Pacific Ocean, and a "severe tropical cyclone" (figure 4.2) in the southwest Pacific and Indian Ocean.

4.5 Where do tropical cyclones form? (The cyclogenesis regions of the world)

In the southwestern Pacific and the Australia region, the climatology of tropical cyclone was produced by Hall et al, (2001). Their study indicated that the Coral Sea region to be the main cyclogenesis region in the South Pacific basin. The tropical cyclones formed in the Coral Sea can move either towards the Australian region or towards the Nadi’s area of responsibility (AoR).

Figure 4.3. Map of all TC basins (the North Atlantic, the Northeast Pacific, the Northwest Pacific, the North Indian, the South Indian, and the South Pacific) with typical track (Source: Vanuatu Meteorological Services).
The western North Pacific (WNP) is different from other cyclogenesis regions because according to Chan (2005), it is the only ocean basin in the world where tropical cyclones (TCs) can form throughout the year. The average number of TCs per year is ~20 which is the highest among all ocean basins where tropical cyclones occur, and exceeds thirty percent (30%) of the global total of ~80 (Chan, 2005). Such high activity mainly results from the frequent occurrence of favorable thermodynamic and dynamic conditions for tropical cyclone development (Gray, 1975). Such occurrence, however, can vary significantly from year to year, which results in a large variation in the annual number of TCs (Chan, 2005).

Figure 4.4. Interannual variations of tropical cyclones over the Northwestern Pacific from 1959 to 2003. The curved line indicates a fourth-order polynomial fit to the time series. The value of $r^2$ in each figure is the percent of variance explained by the polynomial (Source: Chan, 2005).

Chan (2005) identified the annual number of typhoons over the Northwestern Pacific to have very significant interannual and interdecadal variations (figure. 4.4).
Figure 4.5. Average monthly number of tropical cyclones over the Northwestern Pacific based on the data 1959–2003 from the Joint Typhoon Warning Center. Month 1 is January, 2 is February etc (Source: Chan, 2005).

The average monthly distribution of tropical cyclone in the western North Pacific within the 1959-2003 period (figure 4.5) shows the monthly frequency is lowest between January and March, then rises to a peak in August and decreases in the autumn and winter.

4.6 Tropical cyclone in the South Pacific region

The Southwest Pacific islands are very vulnerable to the effect of tropical cyclones. The majority of tropical cyclones occur between November and April. During this period, South Pacific Ocean surface temperatures reaches their maximum (Terry, 2007) coupled with the favorable atmospheric conditions that favor TC formations. The island countries in this region experiences about three to seventeen (3 – 17) cyclones (figure 4.6) in a season, with most during January and February than any other months (Terry, 2007).
In the South Pacific region, the geographical location of an island nation can determine its degree of vulnerability. Not all island nations are vulnerable to TCs in this region but those that are located in cyclogenesis areas or on a route traversed by cyclones especially those located between 160° E and 170° W can be directly impacted. The routes generally taken by tropical cyclone in this region are normally southeast and polewards (Terry, 2007).

TC events generally maintain their southward movement until about 21° S to 25° S then veer to the east and dissipate around 35° S (Basher and Zheng, 1994). This is later confirmed by recent work done by Kuleshov et al (2008). However, tropical cyclone tracks in the South Pacific basin can also be highly erratic, particularly in the Coral Sea region.
Despite the surface environment, surrounding atmospheric and lower stratospheric conditions are known to be the main influences of the formation of a cyclone. The climatic controls of the frequency of tropical cyclones remain poorly understood at the global scale with a lack of understanding as to why the total number of tropical cyclones, hurricanes and typhoons that developed over the world’s oceans each year is about 80 (Terry, 2007). The number of tropical cyclones forming each year can vary widely between a minimum of three and a maximum of seventeen (figure 4.7) tropical cyclones.

![Tropical cyclone frequency between 1969-70 to 2005-06 season](image)

Figure 4.7. Temporal pattern in the numbers of tropical cyclones in the South Pacific arranged in cyclone seasons from 1969-70 to 2005-06. (Source: Terry, 2007).

In a worldwide study of the origins of tropical cyclones over a period of 20 years (1952-1971), Gray (1975) identified the formation of some 213 tropical cyclones in the region extending from the Queensland Coast (150° E) to 155° W. The cyclone occurrence represents 11% of the global total for that period. A map of the distribution of cyclones over 30 years (1939-1969) shows Vanuatu to have the highest number of tropical cyclones (figure 4.8). Subsequent studies (Salinger, 1995 and Holland, 1998) also show that the area wherein Vanuatu lies has the highest density (53) of tropical cyclones in the
southwest Pacific from 1952-1971 using track density grid box while other countries in this region have less than this number.

Figure 4.8. The distribution of cyclones in the southwest Pacific over a period of 20 year (1952-1971). (Source: Gray, 1975).

4.7 Spatial distribution of TC origins and activity in the South Pacific

Tropical cyclones in the southwest Pacific can exhibit large spatial distribution. Here the distribution is primarily controlled by the South Pacific Convergence Zone (SPCZ) and the ocean-surface sea surface temperature (SST). According to Terry (2007), the SST is the primary influence on tropical cyclone incidence to the west of longitude 170° E which becomes progressively cooler from west to east though monsoonal westerlies are also the main contributing factor. For those countries east of longitude 170° E, the SPCZ is the primary control on tropical cyclone origins which indicates that favorable
conditions such as the atmospheric conditions are more important on intra-seasonal basis.

One of the large scale oscillations that affect the spatial distribution of tropical cyclone in the South Pacific region is the El Niño Southern Oscillation (ENSO). A study by Basher and Zheng (1994) identified that during strong negative southern oscillation (SO) events or El Niño period, cyclone activity extends right across the region to the Cook Islands and French Polynesia, with greatest incidence around the dateline and extending east-southeast of Fiji, and low numbers in the Coral Sea.

By contrast, during the positive SO category or La Niña period, most activity is in the south Coral Sea and New Caledonia area, extending to 30° S with relatively little activity east of the dateline. The cyclone incidence pattern shows a north-south variation with the SO, lying at relatively lower latitudes in negative SOI seasons and vice versa during a positive SOI season.

![Figure 4.9. Latitudinal distribution of annual mean cyclone incidence per 2 degree latitude as a function of SO category from 150 degree E to 130 degree W (Source: Basher and Zheng, 1994).](image)

The research by Basher and Zheng (1994) identified the systematic shifts in the distribution of cyclone incidence are similar to those of the South Pacific convergence zone (SPCZ) which lies across this research study area. This is not surprising as
climatological conditions such as large-scale convergence and moisture availability in this area favors tropical cyclone occurrence. This correlation analysis showed significant relationships between tropical cyclone incidence and associated SST and SO indices. In the eastern Pacific, cyclone mean incidence correlated negatively with SOI and Tahiti pressure and positive with the Darwin pressure. In the western Pacific, the cyclone mean incidence correlates most positively to local mean SST and to SOI while correlation with the Darwin pressure is generally weak.

In the western Pacific, the seasonal atmospheric conditions (abundant moisture and convergence) are generally sufficient for cyclone formation and are only weakly dependent on the state of the SOI, leaving oceanic conditions as represented by preseason SST as the main factor that can vary the cyclone incidence.

In contrast in the eastern pacific, the dominant control is not SST but the geographical extent of large scale convergence, which is strongly dependent on the SO (during negative SO episodes, the SPCZ shifts east-northeastwards across this region (east pacific)) in a fashion similar to the cyclone pattern.

4.8 The conditions favoring formation of tropical cyclone

Tropical cyclones occur only in specific parts of the globe specified in figure 4.3 and during specific seasons and is been related to its seasonally dependent climatological conditions. Watterson, Evans and Ryan (1995) and Landsea (2000) pointed out that the climatological conditions favorable to the genesis of tropical cyclone are of three types namely: surface environment influences, surrounding atmospheric influences and lower stratospheric influences. The conditions on the surface environment and surrounding atmosphere which they influence are needed to trigger formation of tropical cyclone includes:
1. Warm ocean waters (of at least 26.5°C) throughout a sufficient depth (at least on the order of 50 m). Warm sea surface temperatures (SSTs) are necessary to fuel the heat engine of the tropical cyclone.

2. An atmosphere which cools fast enough with height such that it is potentially unstable to moist convection. It is the precipitating convection in the form of thunderstorm complexes which allows the heat stored in the ocean waters to be released for tropical cyclone development.

3. Relatively moist layers near the mid-troposphere. Dry mid levels are not favorable for allowing the continued development of widespread thunderstorm activity because entrainment into the thunderstorms dries and cools the rising parcel, reducing buoyancy. Terry (2007) and Gray (1975) emphasize that moisture content is an important factor on which storm formation is dependent especially in the mid-troposphere where relative humidity in the surrounding atmosphere allows more rapid saturation and condensation of moist and rising air than would otherwise occur.

4. A minimum distance of around 500 km from the equator. For tropical cyclogenesis to occur there is a requirement for small amounts of the Coriolis force to provide for near gradient wind balance to occur. Without a substantial Coriolis force, inflow into the low pressure is not deflected to the right (to the left in the Southern Hemisphere) and the partial vacuum of the low is quickly filled.

5. A pre-existing near-surface disturbance with sufficient vorticity and convergence Gray (1975). Terry (2007) labels this condition as a favorable atmospheric environment that is characterized by little disturbance. Tropical cyclones cannot be generated spontaneously. To develop, they require a weakly organized system with sizable spin and low level inflow.

6. Low values (less than about 10 ms⁻¹) of vertical wind shear between the 850 and 200 mb levels Gray (1975). Vertical wind shear is the magnitudes of wind change with height or Terry (2007) expressed it as the gradient of wind velocity with height. Large values of vertical wind shear disrupt the developing tropical cyclone and can prevent
genesis, or, if a tropical cyclone has already formed, large vertical shear can weaken or destroy the tropical cyclone by interfering with the organization of deep convection around the cyclone center. The amount of vertical shear depends on the temperature structure of the air (Terry, 2007). This atmospheric condition has hindered the proper development of many cyclones in cyclogenesis areas.

With the availability of these conditions (the Atmospheric and Oceanic conditions) in cyclogenesis areas, tropical cyclones can form meaning countries within these areas are more susceptible to the formation and impacts of tropical cyclones.

4.9 Tropical cyclone track directions

Tropical cyclones usually migrate from the tropics to the poles. In the northern hemisphere, they move from near to the equator and northwestwards towards the pole while in the southern hemisphere, they move from close to the equator and migrate southeastwards towards the poles but their paths are never straight. The explanation of the poleward drift of TC events is known as the beta effect (Lester et al, 1997).

It has been observed that the movement of TC can be described, to a large extent by the synoptic-scale flow surrounding the cyclone (Chan and Gray, 1982). Terry (2007) discovered from his maps of tropical cyclone tracks in the South Pacific region covering 29 years (1970-1999) that what initially appeared as a jumble of criss-crossing storm paths revealed a major trend in a northwest to southeast orientation in the track alignment (figure 4.10).
Figure 4.10. Chart showing the tracks of all tropical cyclone in the South Pacific during 1990s (Source: Terry, 2007).

As a result of this trend in track alignment, the north and western flanks of high islands in the South Pacific commonly found themselves on the ‘windward’ side in relation to tropical cyclones, because they frequently face into the direction of approaching storms. This is a reversal of the usual situation, because the north and west coast of islands lie on the sheltered side in relation to the dominant Southeast Trade Winds.

Even though cyclones are expected to behave normal in relation to their northwest to southeast track alignment, their paths are never straight (Terry, 2007). Tropical cyclones tracks in the Southwest Pacific often have curves and many of the storm tracks, according to Terry (2007), display wide departure from the more common shapes. Some of the types of departure from normal highlighted are:

- direction contrary to the average trend, for example northeast to southwest track alignment,
- sharp twists and turns in direction
- looping tracks with single or multiple loops
- combination of the above.

4.9.1 Why straight track – A case study of Taiwan

Why some tropical cyclones track straight and others do not is a question of great scientific interest. Jian and Wu, (2005) used a case study of super typhoon Haitang on the Island of Taiwan to illustrate why tropical cyclones may have straight and curved tracks. This case study identified that relative straight tracks are primarily associated with three factors.

1. The larger and stronger storms are less susceptible to topographic deflection. This is because as shown by Jian and Wu (2005), a faster-moving vortex has less time to interact with the terrain and therefore experiences smaller track deflection as it approaches land fall (figure 4.11). A faster moving storm has less time to deflect which is the key mechanism to prevent the looping path.

2. The second factor that contributes to deflection in tropical cyclones is the strength of the steering flow. The steering flow is the wind flow patterns at various levels in the atmosphere around a cyclone system which has a greater influence in the steering of the system. The stronger the steering flow, the lower chances a tropical cyclone track to be deflected (Chan and Gray, 1982). Jian and Wu (2005) mentioned that super typhoon Haitang has a strong steering flow from the north allowing it a smaller southward deflection since the southward steering flow is weaker. Tropical cyclone steering flow is further explain in section 4.10.4

3. The last but equally important factor in producing either a straight or unusual track orientation is the terrain or the landmass. The terrain of the physical land features can have a great influence on tropical cyclone making landfall by either allowing the cyclone to disorganize or be deflected depending on the terrain of a
particular landmass. In the experiment of simulation without the Taiwan terrain (represented by the open circle in figure 4.11), the looping motion disappears which suggests the presence of the Taiwan terrain played a significant role in track deflection. These simulations demonstrate that speed at which a cyclone is traveling at, the steering flow and the terrain are important factors in determining the track orientation of tropical cyclone (Jian and Wu, 2005).

The terrain height of Taiwan at each Grid is reduce to 70%

![Figure 4.11](image)

Figure 4.11. Simulated tracks of (a) H70 (solid circles) and NT (open circles) and (b) Best track of Super typhoon Haitang (Source: Jian and Wu, 2005).

### 4.9.2 Why looping tracks – A case study of Taiwan

In the same research, Jian and Wu (2005) demonstrated that within the same cyclogensis region, tropical cyclone tracks can be straight with unusual track orientation. It must be noted that tropical cyclone tracks are not only straight; records in all cyclogensis regions showed tracks with loops, curvature and other track directions or shapes contrary to the average trend.
The first factor that can cause unusual track orientation is the redeveloping of a weakening tropical cyclone system before making a landfall. The South Pacific region studied by Terry (2007) showed tropical cyclones often had unusual track orientations if they were the remnants of a tropical cyclone redeveloping into a new system where loops rarely occur and can occur in anticlockwise or clockwise directions.

The second factor causing looping tracks is the speed at which a tropical cyclone is travelling. In the case study of typhoon Haitang, Jian and Wu (2005) mentioned that the track differences between the storms of H70 and NT (figure 4.12), as examples, are primarily due to two main causes: first, the storm in A35 is a larger, more intense, and has a more rapidly moving vortex and therefore would be more likely to move across the Taiwan terrain with less track deflection. This factor implies that a faster moving storm has less time to deflect (southward in this case), which is the key mechanism to prevent the looping motion.

Figure 4.12. Simulated tracks of (a) A35 (solid circles) and A35_NT (open circles) and (b) A47 (solid circles) and A47_NT (open circles) (Source: Jian and Wu, 2005).
Secondly, it was also identified using upper level wind charts for super typhoon Haitang that although a low-level northerly jet stream predicted in the western portion of the A35 (with terrain) storm (figure 4.12), the strongest winds associated with the storm are on the eastern side of the storm. In contrast to the A35_NT simulation (no terrain), the wind distribution in the A35 storm has smaller average southward steering (advection), which leads to a smaller southward deflection. These simulations suggest that the two above factors are important for determining the sharp track deflection associated with a typhoon (e.g., Super typhoon Haitang) moving westward toward the east coast of Taiwan (Jian and Wu, 2005). In the South Pacific region, the jet stream plays a big role in directing the movement of tropical cyclones.

In a similar context, the ridge of high pressure in the South Pacific region usually stretching to about 15° S keep a tropical cyclone well-established in the trade wind belt, whereas an advancing trough of low pressure can cause a storm to recurve. Recurvature is the term given to a deflection in the track direction. In the tropical latitudes above 15° S, cyclones often move towards the west with only a slight poleward component. This is because of the existence of the sub-tropical high pressure ridge farther south (Terry, 2007).

With the variations in the curvature and orientation of tropical cyclones track shapes, it is often difficult to make precise track forecasts. The failure in forecasts to capture the curvature in the tropical cyclone tracks emphases that numerical models fail to predict cyclone turning motion most of the time (Chan, Gray and Kidder, 1980). The errors in forecast tracks in turning motions may occur probably as a result of insufficient observational knowledge of the characteristics of the cyclones surrounding environmental flow patterns and their changes as well as the boundary layers of a certain area. If these boundaries layers (terrains and jet stream) are included in models, then tracks forecast errors will be reduced with higher chances of predicting cyclone turning motions. However, a lot of improvement has been done in recent years with respect to track forecast.
4.10 Variations in environmental conditions that affect tropical cyclone activity

4.10.1 Pacific Subtropical High

The subtropical high is one of the main climate drivers in the South Pacific region (figure 4.13 & 4.14). It is a large anticyclone situated in the sub tropics. It is elongated along a west to east axis, thus forming a ridge of high pressure. During the wet months or tropical cyclone season, it is located in higher latitudes compared to its position during the dry months that normally produce a ridge of high pressure further to the north. It is a persistent feature and rarely absent and it influences tropical cyclone to move west because of the easterly winds prevailing on the equatorward side of the subtropical high (Terry, 2007).

In the absence of strong steering currents, or if the subtropical ridge is weak, then coriolis acceleration causes storms to turn in a more poleward direction. On the poleward side of the subtropical ridge, westerly winds steer the path of tropical cyclone back towards the east (Terry, 2007).

4.10.2 South Pacific Convergence Zone (SPCZ), the Inter-Tropical Convergence Zone (ITCZ) and Equatorial trough

Synoptic scale influences have important effects on the environmental steering flows of a tropical cyclone event. The South Pacific Convergence Zone (SPCZ) is one of the most significant and an extensive feature of the atmospheric circulation of the tropical Southern Hemisphere in the summer. It is a broad feature, and is associated with maxima of sea surface temperatures, precipitation, cloudiness, low level convergence (10 m) and a minima of outgoing longwave radiation (Trenberth, 1976). It was also apparent from studies by Trenberth (1976) using satellite imagery in their analysis that the SPCZ changes from a true tropical convergence zone in its western portion to a region with mixed tropical and extra-tropical characteristics at its eastern margin (figure 4.13 & 4.14).
Figure 4.13. The SH summer circulation features in the SW Pacific region (Source: Steiner, 1980).

Figure 4.14. The SH winter circulation features in the SW Pacific region (Source: Steiner, 1980).
Folland et al., (2002) argued that the location of the SPCZ is of great importance to those areas directly south that often receive high precipitation, while locations well away can receive much lower amounts. Tropical cyclones usually develop within these regions of low pressure and from pre-existing tropical disturbance (Terry, 2007). In the South Pacific region the SPCZ is an extension of the equatorial trough from the warm pool region southeastward. This is often responsible for the initiation of tropical depressions and tropical cyclones that are often found embedded within it.

The location of the SPCZ between the Dateline and the longitude of French Polynesia is known to vary systematically with ENSO-related expansions and contractions of the west Pacific warm pool.

It also varies with the phase of the Interdecadal Pacific Oscillation (IPO) (Folland et al., 2002). According to Power et al. (1999), when the IPO raises temperature over the tropical Pacific Ocean, there is not robust relationship between year-to-year Australian climate variation and ENSO. When the IPO lowers temperature in the same region, on the other hand, year-to-year ENSO variability is closely associated with year-to-year variability in rainfall.

Variations in the mean location of the SPCZ are important for South Pacific climate, as precipitation and tropical cyclones can vary strongly with the movement. During the cyclone season (November to April) when the ocean-surface temperatures reach their maximum, the South Pacific Convergence Zone descends to its most southerly annual position where it is often developed as a broad band of active convergence and convection (Terry, 2007).

The SPCZ is linked to the Inter-Tropical Convergence Zone (ITCZ) in the west over the Pacific warm pool and it is maintained by the interaction of the trade winds and disturbances in the mid-latitude westerlies in the east and associated with more rainfall (figure 4.15). It is most active during the southern hemisphere summer months (November - April) which is also the tropical cyclone season.
A century-long time series for the SPCZ from high-quality station mean sea level pressure data from South Pacific Island sites (Suva and Apia) were used to define a proxy index of SPCZ position known as the SPI (Salinger et al., 1995 & Folland et al., 1998). Small displacements in the mean position of the SPCZ are important and the movement of the SPCZ as a result of the influence of ENSO and IPO makes it oscillate between Fiji and Samoa. The location of the SPCZ is defined to be between longitudes 180° W and 170° W (Folland et al., 2002). This gives the mean location of the SPCZ between Fiji and Samoa in a NW - SE direction while the tip of the SPCZ is just over the north of Vanuatu (Steiner, 1980) during the summer. The ITCZ moves south lying across eastern Australia to the Solomon Islands where there is a break in the
continuation of the system. The ITCZ continues again from about 7° N, 172° E as shown in figure 4.13 & 4.14. During enhanced La Niña summers, the SPCZ and ITCZ merge over the area of the Solomon Islands and further south from its mean location positioning it over Vanuatu.

Folland *et al.*, (2002) in their study showed that on average, El Niño events lead to a northeastward movement of the SPCZ, relative to La Niña events (figure 4.16). There is a tendency towards fusion of the ITCZ and the SPCZ in the central equatorial Pacific with enhanced convergence there and in the east tropical Pacific. The analogous behavior of the SPCZ in the warm phase of the IPO (1978–1998) results in a northward shift compared to the cool phase (1958–1975).

![Figure 4.16. Mean SPCZ location as a function of different polarities of ENSO and IPO (Source: Folland *et al.*, 2002).](image)

The positioning of the SPCZ is also influenced by the ENSO phases and studies have identified that the SPCZ is considered to influence TC genesis (Vincent *et al.*, 2009) in three phases that are almost similar to those locations identified by Folland *et al.*, (2002). One and two are 3° north and south of the normal position (normal position is black line in figure 4.17) of the SPCZ while the third location displays peculiar behavior where this climate driver largely departs from its climatological position and is zonally oriented. The latter displacement of the SPCZ occurs only during extreme El Niño years and is zonally oriented around 6° S (asymmetric line figure 4.17).
Figure 4.17. Positions of the SPCZ from GPCP for each class. Red “asymmetric”, orange “positive”, black “neutral” and blue “negative” years. b Total precipitation flux (in Sverdrup) in the SPCZ region (143°E–120°W/0°–30°S) (Source: Vincent et al., 2009).

There is also an interannual shift in the SPCZ location and this variability is mostly characterized by a north-south movement in the 160°W - 160°E region and the western and eastern portions (Vincent et al., 2009). These changes also contribute to the shift in cyclogenesis area within the South Pacific region as shown in figure 4.18 where TC density genesis anomalies were higher in the Coral Sea region during the neutral and negative phase and more to the east of dateline during positive phases of ENSO.
Figure 4.18. “Neutral” class TC genesis density (in number of genesis per 20 years and per 5° × 5° boxes); rectangles delimitate the different regions: 1 Coral Sea, 2 Tuvalu, 3 Fiji and 4 Polynesia. a “Asymmetric”, b “positive”, d “negative” composites of TC genesis density anomaly with respect to the “neutral” case; the thick dashed contour is the isoline four TC/20 years/(5° × 5°) of TC genesis density. Climatological GPCP SPCZ (green dashed line) and composite SPCZ (green line) are reported on each map (source: Vincent et al., 2009).

The systematic variation of the SPCZ is related to the western Pacific warm pool identified by Trenberth (1976) as the location of the SPCZ varies with ENSO-related expansion and contraction of this pool, moving northeast during El Niño events and southwest during La Niña events. Variations in the mean location of the SPCZ are important for South Pacific as tropical cyclone and precipitation can vary strongly with the movement. Such movements can result in more tropical cyclone on either side of the mean location of the SPCZ as it moves northeast during El Niño events and southwest during La Niña events.
4.10.3 ENSO and tropical cyclone

The El Niño Southern Oscillation (ENSO) is a large scale atmospheric circulation pattern that has a substantial impact on the formation and tracks of observed tropical cyclones in TC regions of the globe, including the North Atlantic and the southwest Pacific (Hastings, 1990; Evans and Allan, 1992; Basher and Zheng, 1995; Camargo, 2007). Globally, tropical cyclones are affected significantly by ENSO. ENSO is a fluctuation on the scale of a few years in the ocean-atmospheric system involving large changes in the Walker and Hadley Cells throughout the tropical Pacific Ocean region (Landsea, 2000).

The state of ENSO can be characterized among other features by the sea surface temperature (SST) anomalies in the eastern and central equatorial Pacific. Warming in this region is referred to as El Niño events and cooling are La Niña events. The Southern Oscillation Index (SOI) is the standardized difference in sea level pressure between Tahiti and Darwin in Australia also describes the state of ENSO with high (low) pressures at Darwin and low (high) pressure at Tahiti corresponding to El Niño (La Niña) events, respectively. ENSO greatly alters global atmospheric circulation patterns and it is able to affect tropical cyclone frequencies primarily by ‘altering the lower troposphere source of vorticity and by changing the vertical shear profile’ (Landsea, 2000).

In the southwest Pacific, the average annual number of TC event is about 0.6 over the Coral Seas and Vanuatu areas (figure 4.19). Fewer mean annual TC events spread eastwards up to 150° W and reach further south over New Zealand.
Figure 4.19. Distribution of annual average tropical cyclones through the Australian region and surrounding waters: TC data based on a 36 years period from 1969/70 to 2005/06 tropical cyclone season (Source: Bureau of Meteorology, Australia (BoM)).

During the neutral years, the maximum average annual number of TCs is about 0.6 concentrated more to the Coral Sea and Queensland coast with lesser event numbers diagonally spread not eastward of 150° W (figure 4.20) and just to the northeast of New Zealand. During El Niño years, the TC number increases to the east of the Dateline with an area of maximum annual event average of 0.6 shifting over Vanuatu and towards Fiji islands (figure 4.21) with an especial increase in tropical cyclone occurrence east of 165° E due to the warmer SST over the central eastern Pacific region.
Figure 4.20. Distribution of tropical cyclones during Neutral years through the Australian region and surrounding waters. TC data based on a 36 years period from 1969/70 to 2005/06 tropical cyclone season (Source: Bureau of Meteorology, Australia).

Figure 4.21. Distribution of tropical cyclones during El Niño years through the Australian region and surrounding waters. TC data based on a 36 years period from 1969/70 to 2005/06 tropical cyclone season (Source: Bureau of Meteorology, Australia)
While TC basins within the Pacific region have different annual TC frequency, the influence can be partly forced by direct alterations of the SSTs in the genesis regions. However, ‘most basins experience remote forcing through alteration of the tropospheric flow features’ (Gray, 1975). It is the combination of spatial, temporal and climatological factors that determine how individual tropical cyclone basins will be altered by ENSO.

Past research interest lies in the frequency and intensity of tropical cyclone while recently there has been an increase in studies on the influence of large scale circulation and interseasonal circulation on the lifecycle of tropical cyclones. Most studies confirm that there is linkage between TC and these large scale circulations. Maue (2010) identified global interannual variation in TC frequency and Accumulated Cyclone Energy (ACE) (which also includes duration and intensity) to be a function of observed large scale low frequency modes of ocean-atmosphere climate variability mainly on interannual and longer time scales. The study also demonstrated that TC frequency is also associated with changes or evolution in the characteristics of the ENSO and the Pacific Decadal Oscillation (PDO).

The PDO in its warm (cold) phase during 1977 – 1995 (1958 - 1976) creates a SST warm (cold) background condition in the central and eastern tropical Pacific reducing (increasing) the east – west SST gradient, which locally acts to weaken (enhanced) the Walker circulation action centers (Garcia et al. 2007). These climate drivers modulate the TC genesis location and tracks characteristics which relates to changes in lifecycle duration and intensity.

Nicholls (1990) identified that the tropical cyclones in the vicinity of Australia (90° E to 165° E), are reduced in number during the warm phase (or El Niño) of ENSO. This is also confirmed by R.E and X. Zheng (1995) that tropical cyclone incidences were high in the Coral Sea region (150°-170° E) before the positive SST anomalies and weak positive anomalies of the SOI. The other regions (between 170° E and 130° W) were similar to each other but different to the Coral Sea with high cyclone incidence happening before the negative anomalies of SOI and Tahiti pressure which continue into the cyclone season but with only weak or no SST relationship. Revell and Goulter
(1986) demonstrated that the reduction of Australian region tropical cyclones is compensated by an increase in the South Pacific east of 165° E because of a shift in the center of action in tropical cyclone genesis. There is also a smaller tendency to have the tropical cyclones originate a bit closer to the equator (Revell and Goulter, 1986). The opposite is observed in La Niña events.

It is also identified by Basher, R.E and X. Zheng (1995) that the primary influence on tropical cyclone incidence west of 170° E is the local oceanic conditions represented by SST while to the east of 170° E, it is the eastward extent of favorable atmospheric conditions indicated by the SOI or Tahiti pressure.

The shift in TC frequency is found to be also latitudinal. A study by Sinclair (2001) in the Southwest Pacific identified three out of nine cyclones each year expect to migrate south of 35° S, occurring mostly in March. Storms usually move south, retaining greater intensity when entering the Tasman Sea west of New Zealand than those east of New Zealand where storms decay quickly moving rapidly away to the southeast. During El Niño years, storms that move to middle latitude show ‘stronger zonal motion and occur over a wider range of longitudes than in La Niña years’ (Sinclair, 2001). Storm intensity is only weakly correlated with SST anomalies, suggesting that atmospheric circulation is the dominant influence on storm properties.

There is also a smaller tendency to have the tropical cyclones originate a bit closer to the equator. A reconstruction of storms by NIWA (National Institute of Water and Atmospheric Research Ltd) and supported by BoM that during El Niño and La Niña also show that the vicinity around Vanuatu is still the cyclone hot spot (figure 4.21 & 4.22). This is also supported by Nicholls et al., (1990) that during an ENSO event in the eastern Pacific, the SSTs over the western Pacific are relatively cooler and atmospheric pressure over western Pacific is higher than normal. This leads to a reduced number of cyclones in the Australian region.
Figure 4.22. Distribution of tropical cyclones during La Niña years through the Australian region and surrounding waters. TC data based on a 36 years period from 1969/70 to 2005/06 tropical cyclone season (Source: Bureau of Meteorology, Australia).

The Walker circulation plays an important role in determining ENSO events and this circulation constitute the shift of TC genesis areas. Kuleshov (2009) stated that during ENSO warm phase (El Niño events), this circulation is weakening (this manifests in weakening the easterly trade winds, rise in air pressure over the Indian Ocean, Indonesia and Australia and fall in air pressure over the central and eastern Pacific Ocean) and displacing warm water in the Pacific (i.e. cooling water in the western Pacific and warming water in the central and eastern equatorial Pacific) occur. While during cold phase (La Niña events), the trade winds strengthen, warmer water accumulates in the far western Pacific and cold pool in the eastern Pacific intensifies, resulting in equatorial SSTs being cooler than climatological average.

Beside the El Niño-Southern Oscillation (ENSO), there is another global factor that appears to force changes in tropical cyclones: the stratospheric Quasi-Biennial Oscillation (QBO). QBO is ‘an east-west oscillation of stratospheric winds that encircle the globe near the equator’ (Landsea, 2000). The early progress of the QBO research is an exemplary case of comprehensive atmospheric/climate exploration in which
observation (Reed et al. 1961; Veryard and Ebdon 1961), theory (Lindzen and Holton 1968), and laboratory experiment (Plumb 1977) were integrated to reveal the nature of a complicated phenomenon. Now it is known that the QBO originates from interactions between the mean sheared flow in the stratosphere and the vertically propagating dissipative waves generated in the troposphere (Lindzen and Holton 1968). This oscillation has a distinct effect upon Atlantic (more activity in the west phase), Southwest Indian (more activity in the east phase) and Northwest Pacific (more activity in the west phase) tropical cyclones. The exact mechanism of the stratospheric QBO's influence on tropical cyclones is uncertain and needs further research.

In addition to the global effects of ENSO and QBO, there are also local effects that appear to directly impact tropical cyclone frequency within individual basins. These include variations of local sea level pressures, SSTs and trade wind and monsoon circulations. Gray et al., (1993) have suggested that abnormally low Sea level Pressure (SLP) indicates a poleward shift and/or a strengthening of the Inter-tropical Convergence Zone (ITCZ). He also indicates that low SLP is accompanied by a ‘deeper moist boundary layer and a weakened trade wind inversion’. Moreover, an enhanced ITCZ provides more large-scale, low level cyclonic vorticity to initiate tropical cyclones, thereby creating an environment that is more favorable for tropical cyclogenesis (Gray, 1993). In contrast, above normal SLP tends to be associated with opposite conditions which are unfavorable for tropical cyclogenesis.

One aspect that has been known for decades is the association of a tropical cyclone basin with its generating or a nearby monsoon trough. As previously mentioned, that variations in the Australian monsoonal flow can be associated with changes in tropical cyclone activity such that a strong (weak) monsoon circulation during a cold (warm) phase of ENSO is accompanied by many (few) tropical cyclones. It is also suggested by Revell and Goulter (1986) that variations in the Australian monsoon could alter the tropical cyclone activity, independent of any pronounced ENSO events.

In summary, sea surface temperatures (SST) appears to play the primary role in the genesis regions of tropical cyclone basins and have a ‘direct thermodynamic effect on
tropical cyclones through their influence on moist static stability’ (Landsea, 2000). Pacific SSTs also indirectly influence the vertical shear through its strong inverse relationship with surface pressures in some regions (Gray et al., 1993 and Nicholls, 1990). It is also identified that the interannual SST variations have relatively small or minor contributions toward increasing the tropical cyclone frequency in most basins. Only the ‘Atlantic, Southwest Indian and Australian regions have significant though small, positive associations in the months directly before the tropical cyclone seasons begin’ (Landsea, 1993).

4.10.4 Large scale flow field/The steering flow

A factor that has been considered for forcing interannual variations of tropical cyclone activity as identified by Landsea (2000) is the changes in the "steering flow" in which the storms are surrounded. Steering flow is the pressure level at which the speed and the direction of the surrounding winds best correlate with the track of the storms. Tropical cyclones can be considered to be steered by the ‘surrounding deep layer (the ocean surface to 100 mb) atmospheric flow features’ (Landsea, 2000). The study also suggested that interannual variations in the mid-tropospheric flow fields could help account for both variations in Atlantic basin tropical cyclogenesis and in the tracks of the storms once formed. The mid-tropospheric flow features can also account for sub-regions within the Atlantic basin experiencing more or less activity in any particular year.

In the South Pacific region, the environmental steering is also the primary influence on the motion of a tropical cyclone (Terry, 2007). A majority of tropical cyclones in this region once formed migrate generally eastwards and polewards from their original position due to the upper level wind flow. A recent study by Chand and Walsh (2009) confirmed that 700-500 hPa mean steering flow constitutes the steering of TC forming in the southwest Pacific, between 6° and 18° S, 170° E and 170° W southeastward to the north of Fiji islands and Tongan region by the predominant northwesterly mean flow regime. While cyclones form to the east of date line are usually steered north of the
Samoa region by dominant westerly flow over the genesis area while those that form 5° and 10° S, 170° E and 180° recurve west-southwest of the Fiji Islands.

It is described by Wu and Emanuel (1995) that such steering flow can account for 80% of the variability in the 24-h tropical cyclone motion. Because tropical cyclones are part of the large-scale flow which varies with latitude, defining an appropriate steering current is difficult and there is no unique way to determine the steering flow. It is not clear which is the best definition for steering level and how this definition should differ among different cyclones having different characteristics (storm intensity, size, location, track directions, and track displacements). While other studies showed that the basic current in the middle tropospheric or a deeper layer mean flow may represent the hurricane steering flow, the geostrophic component at layer 700 and 500 mb are found to be equally good in predicting the subsequent 24-h hurricane motion. This level ideal for TC steering is also confirmed by Chan, Gray and Kidder (1980) that it is known for many years that tropical cyclone motion is well related to mid-tropospheric surrounding wind patterns. This study identified that 500 mb (figure 4.23) is the best steering level for direction and 700 mb for tropical cyclone direction and speed respectively.

![500 mb streamlines for the three turn classes at turn time. Open arrows indicate the instantaneous direction of storm motion. Solid arrows indicate the movement of storm during the next 12 h (Source: Chan, Gray and Kidder, 1980).](image)

The steering flow is often associated with such systems as the subtropical high, the monsoon trough and other synoptic features such as the upper-level trough or ridge (Wu
and Kurihara, 1996). It is identified that a hurricane with strong circulation can substantially change the surrounding environment flow field, which can in turn affect the evolution of the track, intensity and structure of the hurricane. The interaction between the tropical cyclone and its environment is nonlinear. Wu and Emanuel (1995) also identified that on average, tropical storms move in the direction with the speed of a steering current and this correlation of flow features applies equally well for different type of storms.

It is also identified by Wu and Emanuel (1995) that most storms move to the right of their steering flows whereas for typhoons in the western north Pacific, there is a leftward deviation from the middle-tropospheric (500 mb) mean flow at middle and higher latitudes but to the right at lower latitudes. This study also revealed that tropical cyclones in the northern hemisphere move about 10° - 20° to the left of the steering flow and those in the southern hemisphere move about 10° to the right with tropical cyclones in general moving about 1 ms⁻¹ faster than the steering flow. This is also confirmed by Wu, Huang and Chou (2004) that wind data at mid-troposphere (700, and 500 mb) correlates best with both the direction and speed of cyclone movement in which on average tropical cyclones in the northern hemisphere move ~10-20° to the left of the surrounding mid tropospheric winds at ~6° radius from the cyclone center in, an approximate opposite directional deviation occurs for cyclones in the southern hemisphere.

Wu, Huang and Chou (2004) in their research on typhoons in the northwest Pacific, identified that typhoons over the western North Pacific often move westward or northwestward because of the dominating steering flow associated with the Pacific subtropical high (SH). However, in some cases during the late season as typhoons approach about 130° E, typhoons may slow down, stall, or even recurve because of the weakening of the SH, as well as the strengthening of the continental high (CH) over mainland China and/or the presence of the deep mid-latitude baroclinic wave/trough, thus making the forecast difficult.
Despite the availability of literature on the environmental conditions affecting lifecycle and behavior of tropical cyclone, the existing ones do not provide a comprehensive answer to the question of how the environmental dynamics influence the of tropical cyclone track sinuosity in the South Pacific region and the global as a whole.

4.11 Physical processes responsible for the significant track deflection and looping motion

So far it appears that there is very little literature on physical processes that are responsible for track deflection in the South Pacific. Therefore this study refers to typhoon Haitang in Taiwan as an example to demonstrate the concept. The location may be different but similar processes can apply in South Pacific region.

4.11a Land mass /Terrain – A case study of Taiwan

The behavior of tropical cyclones is often affected by many factors including various environmental conditions surrounding them. Although the interaction of a tropical cyclone with the terrain is one factor of interest, many of the details of this interaction are not well understood. Influences of topography on the movement of tropical cyclones have been observed and authors also note the rapid decay of storms as they interact with the mountain topology of the region. Another important quantity often affected by the presence of mountain terrain apart from track and speed, is the storm rainfall distribution (Bender, Tuleya and Kurihara, 1986)

A research carried out by Bender, Tuleya and Kurihara (1986) on the islands of Japan, Taiwan and Madagascar showed the significant orographic effects on the behavior of tropical cyclones have apparently been caused by island mountain ranges. Many of the regions in the world with the greatest tropical cyclone threat such as Taiwan, Japan, or Madagascar are island areas which contain significant mountain terrain (Bender, Tuleya
and Kurihara, 1986). The island topology affects the basic flow field. It also directly influences the structure of the tropical cyclones when they pass over or nearby the region. The combination of the above two effects yields changes in the movement and structure of the tropical cyclones (Bender, Tuleya and Kurihara, 1986). After a TC making landfall and encountering the high mountain ranges, the surface pressure minimum undergoes rapid filling. The surface low may continue to move with the upper-level vortex as it crosses the mountain range (Bender, Tuleya and Kurihara, 1986). The latent heat supply, as well as the vertical coherence of the storm system are important factors in the determination of the intensity change of the storms near and over the islands. When dry air is advected from the mountains regions into the storm area, the storm may exhibit a weakening tendency even well before landfall. The weakening may be enhanced if the vertical axis of the storm system is forced to tilt at the same time. After leaving the island and moving over open ocean, the storms generally reintensify if a vertically coherent structure is present, or, otherwise, not until it is reestablished several hours later (Bender, Tuleya and Kurihara, 1986).

Recently, the research of TC landfall has received much attention, especially as one of the primary foci in the U.S. Weather Research Program. During the landfall period, the TC inner core often has a highly asymmetric distribution of strong winds and deep convection. When the TC approaches a region with complex terrain, the asymmetric structures may become more complicated and result in various types of track deflections (Jian and Wu, 2005). A detailed investigation of such track deflections is of great importance to hazard mitigation because the most severe damage appears to be highly related to the landfall location and the landfall time especially the coastal areas where it is the most vulnerable areas for natural disaster (Xiao et al, 2010). The direct economic losses and casualties caused by TCs making landfall show a significant increasing trend cause by three factors: wind, storm surges, and rain (Xiao et al, 2010).

Recent studies by Jian and Wu (2005) have shown that storms of different intensities are steered by different atmospheric steering flows (e.g., shallower for weaker and deeper for stronger storms) and that depends on the storm size. Larger storm move faster and
have earlier landfall. A large number of the past studies have revealed that the weaker and slower-moving TC is more susceptible to the topographic deflection. By contrast, more intense and rapidly moving tropical cyclones are more likely to move across an island with a continuous track. In the simulation without the Taiwan terrain, the looping motion disappears, which suggests that the presence of the Taiwan terrain plays a significant role in the track deflection (figure 4.11 & 4.12).

Figure 4.11 demonstrated that when TC Haitang was about 60 km east of Taiwan, the low-level flow on the western side of storm center accelerated because the air parcels originate from a relatively wider area. There was a channeling effect as the inner-core circulation of the approaching typhoon is constrained because of the presence of the Taiwan terrain. Through the channeling effect, a low-level northerly jet forms in the western quadrant of the storm that eventually becomes the strongest winds of the storm. The asymmetric winds induce a southward advection flow that causes the storm to turn sharply southward. These simulations demonstrate that the advection flow caused by the inner-core asymmetric winds is important in causing the looping motion of Haitang prior to the landfall (Jian and Wu, 2005). Sensitivity experiments in which the Taiwan terrain is artificially modified indicate that as the terrain height decreases, the magnitude of the storm-track deflection is reduced. These simulations confirm that the high terrain in Taiwan plays a critical role in inducing the strong low-level northerly jet to the west of the center of Haitang, and thus a southward advection flow that leads to the southward drift (Jian and Wu, 2005) and the influence can be the same in any island in the Pacific with higher terrain.

4.12 Impacts of tropical cyclone

The factors considered for influencing the interannual variation of tropical cyclone activities are of natural cause but recent research has identified that enhanced global warming can impact tropical cyclones. The impacts can be seen as a rapid increase in economic damages and disruption of rapidly developing coastal communities over the past few decades. The damages from a TC event can be related to the associated rainfall,
wind speed and lighting, thunder and storm surge activity from a system (Xiao et al., 2010). The sectors that are most susceptible to these impacts include the economic driven sectors, infrastructure, biodiversity and the livelihood of people. Recent detailed TC studies such as Xiao et al (2010) and Callaghan (2003) emphasis on the vulnerability of coastal areas which are more susceptible to TC landfall impacts have greatly improved our understanding of tropical cyclones and their impacts.

The damages and losses are representative to island nation’s vulnerability to tropical cyclones and the South Pacific region is becoming more prominent because the fastest population growth is in the island nation’s coastal areas. Vulnerability depends on geographical location of island countries with regards to cyclone genesis areas and also the ‘sensitivity of the islands affected’ (Terry, 2007). The countries to the west of the dateline are more vulnerable than those to the east to tropical cyclones. The vulnerability magnitude of effects is also a ‘function of the severity of storm’ (Terry, 2007) in which storm frequency and intensity plays a very important role. However, it must be stated that ‘understanding tropical cyclone genesis, development and associated characteristic features has been a challenging subject in meteorology in the past several decades’ (Landsea et al., 1998) but with recent study in the South Pacific, there are positives that can be drawn out to improve tropical cyclone science in this region that will greatly improve the forecasting level and eventually safeguard the livelihood of people.
4.13 Climate Change and tropical cyclone

A tropical cyclone is a natural event influenced by natural climate controls and any substantial effect of global warming on ENSO would therefore likely have an impact on the regional climatology of tropical cyclone formation in any cyclogenesis region. Recently, studies showed ENSO’s changed in character to a predominance of El Niño conditions, the extreme phase of which appears to coincide with an increase in global temperature records. The two most intense El Niño events in more than a century occurred in 1982-83 and 1997-98 (Gergis and Fowler, 2005). With these characteristic changes, the influence will also impact the pattern of TC activity.

Tropical cyclone frequency and intensity often change over the years and it is believed that these changes are impacted by climate change. Recent research such as Grossmann et al (2011) argue that the presence of a possible climate change signal in TC activity is difficult to detect because interannual variability necessitates analysis over longer time
than available data allow and future TC activity hindered by computational limitations and uncertainties about changes in regional climate, large scale patterns, and TC response. Some other climate change scientists argue that the risk of having more intense tropical cyclones in some cyclone genesis regions is high. This view is supported by Klotzbach (2006) that Northern Hemisphere Category 4 - 5 hurricanes have remained almost the same between the two ten-year periods, and an increase in Category 4 - 5 hurricanes has been observed in the Southern Hemisphere (table 4.1). Most of this Southern Hemisphere increase occurred in the first five years of the data set, and since the early 1990s, as satellite observational technology continued to improve, there has been no continuation of this trend; even though global SSTs and oceanic heat content have continued to rise (Klotzbach, 2006).

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Table 4.1. The number of Category 4–5 hurricanes by individual TC basin, for the North Atlantic and the Northeast Pacific, for the Northern Hemisphere, the Southern Hemisphere and the globe by ten-year periods since 1986 (Source: Klotzbach, 2006).
Chapter: 5. RESULTS

5.1 Introduction

There are different sinuosity values for tropical cyclone tracks and each individual event is unique in its track shape and sinuosity value. This study establishes that TC events have tracks that are fairly straight or those that display complex looping tracks or that followed relatively long and curvy tracks, or backtracked and decayed relatively near their starting points. These track behaviors are categorized into four different groupings that this study uses in analyzing their spatial and temporal changes. This chapter focuses on the different track sinuosity values calculated from the tropical cyclone database compiled by this research, and how this study comes up with a particular name for each group depending on the characteristics of tracks. The second part describes the spatial and temporal relationship of TC track sinuosity with two case studies (Vanuatu AoR and year 1990-2000 period) while the last part will focus on the relationship between TC sinuosity values and different ENSO indices.

5.2 Categories of tropical cyclone track sinuosity

The total number of TCs that have occurred in the South Pacific region during the thirty nine year period (1970-2008) is three hundred and forty six (346) of which two hundred and eighty four (284) originated from the FMS AoR while fifty nine tracks (59) originated outside but migrated into this area. From those that migrated into FMS AoR, in category one, there are twenty seven (27), twenty (20) in category two, eight (8) and four (4) tracks in categories three and four respectively and all account for about nineteen percent. The track sinuosity categories (1-4) are defined in section 5.2.1 to 5.2.4. From the total number of TCs, figure 5.1(A) shows nineteen TCs as the highest number with sinuosity value of 1.02 while the lowest TC frequency is one where majority with sinuosity greater than 2.0 (figure 5.1D). The other sinuosity values have between one and fourteen TCs events (figure 5.1).
A. Distribution of sinuosity in category one  

B. Distribution of sinuosity in category two

C. Distribution of sinuosity in category three  

D. Distribution of sinuosity in category four

Figure 5.1. Distribution of measured sinuosity values in (A) category one (B) category two (C) category three and (D) category four.

The TC track sinuosity values range from one (1) to no fixed upper limit and that depends on the track shape. One is the lowest sinuosity value for a straight track while the upper limit or the highest value in this study is fifty two (52). The mean sinuosity value of all tropical cyclones in the FMS AoR is 1.50 with a standard deviation of 3.08 (table 5.1).
Table 5.1. Results of statistic analysis of FMS TC track sinuosity.

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<tbody>
<tr>
<td>System Count:</td>
<td>284</td>
</tr>
<tr>
<td>Minimum sinuosity value:</td>
<td>1</td>
</tr>
<tr>
<td>Maximum sinuosity value:</td>
<td>52.55</td>
</tr>
<tr>
<td>Sinuosity Sum:</td>
<td>424.22</td>
</tr>
<tr>
<td>Sinuosity Mean:</td>
<td>1.50</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>3.80</td>
</tr>
</tbody>
</table>

A. Tropical cyclone Priscilla (1970) track as an example of sinuosity category one (1.0-1.09).
B. Tropical cyclone Vania (1994) track as an example of sinuosity category 2 (1.10-1.49).
C. Tropical cyclone Abigail (1982) track as an example of sinuosity category 3 (1.50-1.99).
D. Tropical cyclone Betty (1985) track as an example of sinuosity category 4 (≥2.0).

Figure 5.2. Map showing examples of track in sinuosity (A) one (B) two (C) three and (D) four.
5.2.1 Category one

There are one hundred and fifteen (115) tracks in sinuosity category one (1.00-1.09) which are fairly straight similar to the TC event in figure 5.2(A). The mean sinuosity value for this category is 1.04 with a minimum and maximum value of 1 and 1.09 respectively. The standard deviation is 0.03 (table 5.2). These tracks are evenly spread across the region from 160° E to 130° W (figure 5.3A) using the 180° meridian line as the center of the AoR and starting point of each event is counted.

<table>
<thead>
<tr>
<th>Count:</th>
<th>115</th>
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</thead>
<tbody>
<tr>
<td>Minimum:</td>
<td>1</td>
</tr>
<tr>
<td>Maximum:</td>
<td>1.09</td>
</tr>
<tr>
<td>Mean:</td>
<td>1.04</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 5.2. Results of statistical analysis of sinuosity values in category one.

The tracks have a distinct northwest to southeast migration route with a mean bearing of 149.25°. The bearing of a track is taken from the start point to the finishing point and provides a representation of how tracks behave during their lifespan. Those in this category have travelled at a mean global area covered of about 197.50° which is the second highest area covered to tracks in sinuosity category two (table 5.3).

<table>
<thead>
<tr>
<th>Count:</th>
<th>115</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bearing:</td>
<td>30.47°</td>
</tr>
<tr>
<td>Maximum bearing:</td>
<td>276°</td>
</tr>
<tr>
<td>Mean bearing:</td>
<td>149.25°</td>
</tr>
<tr>
<td>Mean Global area covered:</td>
<td>197.50°</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>41.71°</td>
</tr>
</tbody>
</table>

Table 5.3. Results of statistical analysis of track bearing for sinuosity category one.
A. Map of TC track with sinuosity in category one

B. Map of TC track with sinuosity in category two.

C. Map of TC track with sinuosity in category three.

D. Map of TC track with sinuosity in category four.

E. Map of all TC tracks in the FMS AoR

Figure 5.3. Map of TC tracks in sinuosity category (A) one (B) two (C) three (D) four and (E) all combine in the FMS AoR.
5.2.2 Category Two

There are one hundred and seventeen (117) TCs in this category (1.10-1.49) that are straight with little curves extending from Coral Sea region to about 130° W (figure 5.3B). The average sinuosity value for tracks in this category is 1.24 with the minimum and maximum values of 1.1 and 1.49 respectively (table 5.4). The highest concentration of these tracks is from 160° E to about 180° E which is around Vanuatu and Fiji area.

<table>
<thead>
<tr>
<th>Count:</th>
<th>117</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum:</td>
<td>1.1</td>
</tr>
<tr>
<td>Maximum:</td>
<td>1.49</td>
</tr>
<tr>
<td>Mean:</td>
<td>1.24</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 5.4. Results of statistical analysis of sinuosity in category two.

The average bearing of tracks in this sinuosity category is 164.28° that is to the south southeast direction from their point of origin and covered a mean global area of 246.27° which is the highest area covered by TC tracks in all four categories in the FMS AoR (table 5.5).

<table>
<thead>
<tr>
<th>Count:</th>
<th>117</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bearing:</td>
<td>73.12°</td>
</tr>
<tr>
<td>Maximum bearing:</td>
<td>237.82°</td>
</tr>
<tr>
<td>Mean bearing:</td>
<td>164.28°</td>
</tr>
<tr>
<td>Mean Global area covered:</td>
<td>246.27°</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>33.55°</td>
</tr>
</tbody>
</table>

Table 5.5. Results of statistical analysis of track bearing for sinuosity category two.
5.2.3 Category three

This sinuosity category (1.49 – 1.99) consist of thirty five (35) TC tracks that compose a much shorter with more curvatures character compared with those in the previous two categories and have mean sinuosity value of 1.67 with minimum and maximum value of 1.50 and 1.85 (table 5.6). The concentration of these tracks is from the Coral Sea to Vanuatu area (figure 5.3C).

<table>
<thead>
<tr>
<th>Count:</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum:</td>
<td>1.50</td>
</tr>
<tr>
<td>Maximum:</td>
<td>1.85</td>
</tr>
<tr>
<td>Sum:</td>
<td>58.28</td>
</tr>
<tr>
<td>Mean:</td>
<td>1.67</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 5.6. Results of statistical analysis of sinuosity in category three.

The mean track bearing in this category is 164.15° which is still a north to south southeast orientation to those in category one and two but it is 0.13° lesser than the bearing of tracks in category two. The minimum and maximum track bearing is 103.95° and 242.45° respectively and the tracks covered a mean global area of 189.30° which is third highest in the four sinuosity categories (table 5.7).

<table>
<thead>
<tr>
<th>Count:</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bearing:</td>
<td>103.95°</td>
</tr>
<tr>
<td>Maximum bearing:</td>
<td>242.45°</td>
</tr>
<tr>
<td>Mean bearing:</td>
<td>164.15°</td>
</tr>
<tr>
<td>Mean Global area covered by tracks:</td>
<td>189.30°</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>26.73°</td>
</tr>
</tbody>
</table>

Table 5.7. Results of statistical analysis of track bearing for sinuosity category three.
5.2.4 Category four

This last category consists of tracks with sinuosity value of greater or equal to 2.0. It contains seventeen (17) tracks that have more curvatures than those in other sinuosity categories and have a mean sinuosity value of 5.93 with a minimum value of 2.08 and maximum of 52.55 (table 5.8). The concentration of these tracks is from the Coral Sea to Vanuatu area (figure 5.3D).

<table>
<thead>
<tr>
<th>Count:</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum:</td>
<td>2.08</td>
</tr>
<tr>
<td>Maximum:</td>
<td>52.55</td>
</tr>
<tr>
<td>Mean:</td>
<td>5.93</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>11.69</td>
</tr>
</tbody>
</table>

Table 5.8. Results of statistical analysis of sinuosity in category four.

These tracks migrated within a global area of 160.75° smaller than the first three sinuosity categories and have a mean bearing of 172.25° that is a north to south orientation (table 5.9).

<table>
<thead>
<tr>
<th>Count:</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bearing:</td>
<td>65.56°</td>
</tr>
<tr>
<td>Maximum bearing:</td>
<td>340.28°</td>
</tr>
<tr>
<td>Mean bearing:</td>
<td>172.25°</td>
</tr>
<tr>
<td>Mean Global area covered:</td>
<td>160.75°</td>
</tr>
<tr>
<td>Standard Deviation:</td>
<td>69.65°</td>
</tr>
</tbody>
</table>

Table 5.9. Results of statistical analysis of track bearing for sinuosity category four
5.3 Spatial sinuosity analysis

5.3.1 Monthly spatial analysis

The monthly spatial spread of TC tracks shows high concentration of TC events in sinuosity category two to four over the western end of FMS AoR during the month of January and March while evenly spread across the region during the other months. During low TC frequency months (May, June and October), TCs with sinuosity category two and above occurs more to the western end of the Pacific (figure 5.4 E, F & G).
Figure 5.4. TC tracks in the four different sinuosity categories for (A) January (B) February (C) March (D) April (E) May (F) June (G) October (H) November and (I) December.
5.3.2 Annual and decadal spatial analysis

The decadal spatial spread of TC track frequency in the different sinuosity categories depicts a high concentration of tracks to the western end of the Pacific region during the 1970s especially for those in sinuosity category two to four. During the 1980s, tracks in sinuosity category two and three occurred further east to about 130° W compared to the previous decade where TCs occurred only up to 150° W and only one event with such sinuosity occurs in that location (figure 5.5B). During the 1990s, concentration of TC tracks in sinuosity category two, three and four are to the west of FMS AoR especially over Vanuatu to Coral Sea area (figure 5.5C) while during 2000s, tracks are evenly spread across the region with sinuosity categories three and four concentrated over Vanuatu to Fiji area (figure 5.5D).

Figure 5.5. TC tracks during (A) 1970s (B) 1980s (C) 1990s and (D) 2000s in four sinuosity categories from the FMS AoR.
Further analysis shows tracks of sinuosity category four starting further west of the dateline with an average mean starting longitude of 173.4° E with category one, two and three (figure 5.6). However, the latter two sinuosity categories (two and three) have TCs starting furthest east with the lowest mean starting latitude of -14.4° S and -14.9° S compared to category one and four with tracks starting at mean latitude of -15.5° S and -16.7° S.

![Table 5.10](image)

Table 5.10. Statistics of all FMS TCs.

Table 5.10 shows mean positions of tracks in each sinuosity category with mean track length, global coverage area, mean bearing and sinuosity. Tracks in sinuosity categories one and two have mean track length of 2158.6 km and 2565.5 km showing an increasing trend but decreases for tracks in sinuosity category three and four. This trend is similar to that of global mean area covered by tracks in each sinuosity groupings with the lowest mean global area cover of 189.3° and 160.7° respectively for tracks in category three and four. The more sinuous a track is, the lesser mean global area it covers. However, mean bearing increases as sinuosity increases (table 5.10).

Although tracks in sinuosity categories one, two and three though have different mean starting positions, they usually end at almost the same area within 183° E - 185° E and 28° S and 32° S (figure 5.6). Meanwhile tracks in sinuosity category four usually start...
west (173.4° W) and end furthest to the west (178.5° W) of dateline (figure 5.6) compared to other tracks in other categories.

5.4 Tropical cyclone track temporal sinuosity analysis

5.4.1 Monthly sinuosity analysis

From the two hundred and eighty four TC tracks in the FMS AoR, more than twenty four percent (24.6%) or seventy (70) tracks occurred during the month of January representing the highest TC frequency during the whole cyclone season (October to June), followed with February, March, December, April, November, May, October and June (table 5.11).
<table>
<thead>
<tr>
<th>Month</th>
<th>TC Number</th>
<th>Category one</th>
<th>Category two</th>
<th>Category three</th>
<th>Category four</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>%</td>
<td>Total</td>
<td>%</td>
<td>Total</td>
</tr>
<tr>
<td>January</td>
<td>70</td>
<td>24.6</td>
<td>23</td>
<td>32.9</td>
<td>31</td>
</tr>
<tr>
<td>February</td>
<td>65</td>
<td>22.9</td>
<td>29</td>
<td>44.7</td>
<td>21</td>
</tr>
<tr>
<td>March</td>
<td>54</td>
<td>19.0</td>
<td>19</td>
<td>35.2</td>
<td>27</td>
</tr>
<tr>
<td>April</td>
<td>24</td>
<td>8.5</td>
<td>13</td>
<td>54.2</td>
<td>8</td>
</tr>
<tr>
<td>May</td>
<td>8</td>
<td>2.8</td>
<td>3</td>
<td>37.5</td>
<td>4</td>
</tr>
<tr>
<td>June</td>
<td>2</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>October</td>
<td>5</td>
<td>1.8</td>
<td>2</td>
<td>40</td>
<td>2</td>
</tr>
<tr>
<td>November</td>
<td>15</td>
<td>5.3</td>
<td>8</td>
<td>53.3</td>
<td>4</td>
</tr>
<tr>
<td>December</td>
<td>41</td>
<td>14.4</td>
<td>18</td>
<td>43.9</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 5.11. Frequency and percentage of tracks in the four sinuosity categories.

During the month of January, a majority of the tracks (thirty one tracks or 44.3%) have sinuosity values of 1.10-1.49 (category two) while a majority (44.7%) of tracks in the month of February have sinuosity values of 1.0-1.09 (category one). The month of March has fifty percent (50%) of tracks with sinuosity values of 1.10-1.49 (category two) while April has more TCs with sinuosity values of 1.0-1.09 (category one). May and June have more tracks in sinuosity category two while October and November have more category one and December has both categories one and two (table 5.11).

The month of January has a mean sinuosity value of 2.05, February 1.36, March 1.29, April 1.21, May 1.28, June 1.38, October 1.30, November 1.46 and December 1.27 (table 5.13). Therefore the highest mean sinuosity value is in the month of January while lowest track sinuosity value can occur in April (table 5.12).
<table>
<thead>
<tr>
<th>Month</th>
<th>Min</th>
<th>Max</th>
<th>Sum</th>
<th>Mean</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1.01</td>
<td>52.55</td>
<td>143.74</td>
<td>2.05</td>
<td>6.10</td>
</tr>
<tr>
<td>February</td>
<td>1</td>
<td>5.53</td>
<td>88.46</td>
<td>1.36</td>
<td>0.65</td>
</tr>
<tr>
<td>March</td>
<td>1</td>
<td>2.96</td>
<td>69.74</td>
<td>1.29</td>
<td>0.35</td>
</tr>
<tr>
<td>April</td>
<td>1.01</td>
<td>2.11</td>
<td>28.94</td>
<td>1.21</td>
<td>0.26</td>
</tr>
<tr>
<td>May</td>
<td>1.06</td>
<td>1.83</td>
<td>10.21</td>
<td>1.28</td>
<td>0.28</td>
</tr>
<tr>
<td>June</td>
<td>1.34</td>
<td>1.41</td>
<td>2.75</td>
<td>1.38</td>
<td>0.04</td>
</tr>
<tr>
<td>October</td>
<td>1.02</td>
<td>2.08</td>
<td>6.51</td>
<td>1.30</td>
<td>0.40</td>
</tr>
<tr>
<td>November</td>
<td>1</td>
<td>4.51</td>
<td>21.96</td>
<td>1.46</td>
<td>0.91</td>
</tr>
<tr>
<td>December</td>
<td>1</td>
<td>4.24</td>
<td>51.91</td>
<td>1.27</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 5.12. Results of monthly TC sinuosity values.

The likely month for TC tracks having sinuosity values in category one and four is during the month of February (figure 5.7 A & D), while the month of January have more category two and three (figure 5.7B & C). The month with the lowest number of TCs from all sinuosity categories was during the months of June with either zero or one TC event. The average monthly sinuosity values against time (months) during the thirty nine year period shows a declining trend with \( r^2 = 0.222 \) which is not significant (figure 5.7F).
Figure 5.7. Monthly distribution of TC tracks in sinuosity category (A) one (B) two (C) three (D) four (E) combine and (F) monthly average.
5.4.2 Annual sinuosity analysis

The highest TC frequency in sinuosity category one during a single year occurred in 1980 and 1987 with seven (7) TCs (figure 5.8A). There is a period of elevated occurrence during 1970s and towards the end of 1990s to 2000s while during 1982, 1988, 1991 and 1995, there are no TC that has sinuosity values less than 1.10 (or in sinuosity category one) (figure 5.8A). There are five years from the thirty nine that have no TCs with this sinuosity value. Overall, there is a declining trend in time series of TC frequency in this sinuosity category with $r^2 = 0.105$ which is not significant (figure 5.8 A). Sinuosity category two recorded the highest number of years (36) with TC that have sinuosity values between 1.10-1.49 with only three years with no event (figure 5.8 B). There is a period of more TC occurrence with this sinuosity value range during the early 1980s to middle of 1990s while there is less occurrence of TC during the 1970s and 2000s. The overall trend for this sinuosity category is negative with $r^2 = 0.006$ which is also a less significant change (figure 5.8B).

![A. Frequency of tracks in sinuosity category one](image1.png)

![B. Frequency of tracks in sinuosity category two](image2.png)
On the same note, there is almost no trend recorded in the number of TC in sinuosity category four versus time in years with $r^2 = 0.001$ (figure 5.8 D). The highest number of TC with sinuosity in this category is two (2) recorded during 1971 and 2006 (figure 5.8 D). Out of the thirty-nine years, only fifteen of those years recorded TC tracks with sinuosity in this category while twenty-four have no TC events.

Sinuosity category three, on the other hand, has an increasing trend of TC occurrence with time in years with $r^2 = 0.073$ (figure 5.8 C). This is a less significant trend but a
positive one. During 1983 and 1992, there are three TCs that accounts for the highest number of TC per year while there are periods of high occurrence during 1990s and 2000s (figure 5.8C). This sinuosity category recorded the second highest number of years (14) with no TC event. Time series of annual average TC track sinuosity records an increasing trend ($r^2 = 0.141$) with increasing mean TC sinuosity during early to mid-1990s and from 2000s onwards (figure 5.8F).

### 5.4.3 Decadal sinuosity analysis

The period from 1980 to 1989 which is a ten year period has the highest number of TCs with eighty seven (87) events followed with the 1990s (seventy six TCs), then the 1970s (seventy TCs) and lastly 2000 - 2008 with fifty one TCs (table 5.13). The total number of TCs from the 2008-09 to 2009-10 season is twelve (12) bringing the total to sixty three (63) TCs altogether during the 2000 decade and that figure is still lower than the other decades.

During the 1970s and 2000s, a majority of TC tracks have sinuosity values in category one with fifty and thirty seven percent respectively while the 1980s and 1990s have TC tracks with sinuosity values in category two (table 5.13) with more than forty four and forty six percent. The third and fourth sinuosity categories account for between five and twenty percent of TC in each decade.

<table>
<thead>
<tr>
<th>Decade</th>
<th>TC Number</th>
<th>Category one</th>
<th>Category two</th>
<th>Category three</th>
<th>Category four</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>%</td>
<td>Total</td>
<td>%</td>
<td>Total</td>
</tr>
<tr>
<td>1970-1979</td>
<td>70</td>
<td>24.6</td>
<td>35</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>1980-1989</td>
<td>87</td>
<td>30.6</td>
<td>35</td>
<td>40.2</td>
<td>39</td>
</tr>
<tr>
<td>1990-1999</td>
<td>76</td>
<td>26.8</td>
<td>26</td>
<td>34.2</td>
<td>35</td>
</tr>
<tr>
<td>2000-2008</td>
<td>51</td>
<td>18.0</td>
<td>19</td>
<td>37.3</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 5.13. Tropical cyclone decadal frequency in each sinuosity category since 1970.
The highest mean decadal sinuosity value is during the 1990s with 1.99, followed with 2000s with 1.39, 1.33 in 1980s and 1.24 in 1970s. The maximum average sinuosity value is recorded during the 1990s follow by 1980s, 2000s and 1970s (table 5.14).

<table>
<thead>
<tr>
<th>Decade</th>
<th>Sinuosity values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>1970-1979</td>
<td>1</td>
</tr>
<tr>
<td>1980-1989</td>
<td>1</td>
</tr>
<tr>
<td>1990-1999</td>
<td>1</td>
</tr>
<tr>
<td>2000-2008</td>
<td>1.01</td>
</tr>
</tbody>
</table>


The highest number of TCs in a decade with sinuosity category one is recorded during both the 1970s and 1980s with thirty five (35) TCs each while the lowest frequency was recorded during the 2000s. In sinuosity category two, the 1980s also recorded the highest TCs events with thirty nine (39) while the lowest (eighteen) recorded in the 2000s (table 5.13). Sinuosity category three has the highest TC frequency in the 1990s and the lowest in the 1970s. There is no big change in the number of TCs in sinuosity category four during the four decades with the highest TC frequency of five recorded during the 1980s and lowest with four events in other three decades (figure 5.9).
Figure 5.9. Decadal distribution of tropical cyclone tracks in sinuosity category (A) one (B) two (C) three (D) four (E) combine and (F) decadal average.
The z-score analysis is calculating the difference in sinuosity values from a particular time. For example, the sinuosity difference in the month of February from January. Any z-score value that is positive/negative provides an increasing/decreasing trend. The analysis provides a trend from the previous value either for a month, year or decade. In figure 5.10A, there is a general declining trend in TC frequency (with reference to the month of January) for sinuosity category one and three while increasing in the other two categories. The lowest negative change \((z = -1.25)\) is recorded in the month of June for sinuosity category one. However, generally there is a positive change in TC frequency during the months of February, March, October, November and December for all sinuosity categories while negative change occur usually after the months of February or March (figure 5.10A and 7.1).

Annually, the highest positive change in TC numbers in sinuosity category one is in 1987 with z-value of 2.16 while the lowest change is during years with no TC events (figure 5.10B). In sinuosity category two, the highest increase in TC frequency is during 1982 and 1987 with \(z = 2.18\) while the lowest during 1980, 1995 and 2002 with \(z = -1.63\). In sinuosity category three, there is positive change in TCs frequency during 1983 and 1992 with \(z = 2.47\) and during 1972 and 2006 with z value of 2.62 (figure 5.10B and 7.2C).

The decadal changes in TC frequency shows positive change from 1970s to 1980s for TCs in sinuosity category two and four and a negative change till 2000s with z values of -0.5 and -1.18. The number of TCs in sinuosity category three has a positive change \((z = 1.01)\) from 1980s to 1990s then poses a much lower positive change \((z = 0.56)\) to 2000s. Category one shows z values remain constant at 0.81 for the two first decades then decline thereafter (figure 5.10C and 7.3A).
Figure 5.10. Z-score test for (A) monthly (B) annual and (C) decadal changes in tropical cyclone frequency in each sinuosity category.
5.5 Regression and correlation analysis

5.5.1 Normalized TC track sinuosity and Coupled ENSO Index (CEI)

In the previous few sections in this chapter, a description of TC sinuosity over time and space has been investigated. In the next three sections, this study will examine the relationships of track sinuosity to ENSO indices such as CEI, SOI and Niño 3.4 (SST) using monthly values. In case where a TC event occurred during two months, the average value of the index is used. Normally, the higher value of the correlation coefficients between the different ENSO indices and sinuosity indicates greater influence or primarily related to this index.

Generally when CEI value is higher/lower, the SOI and Niño 3.4 are well/poorly coupled or correlated. The time series of monthly sinuosity value and CEI in figure 5.11 shows positive CEI during 1971, 1974-75, 1984-86, 1988, 1996 and 2000-01 with the highest value recorded during 1988 with 3.37. Negative CEI values were recorded during 1972, 1983, 1987, 1991 and 1998 with the lowest values -4.60 recorded in 1982 (figure 5.11).

Figure 5.11. Tropical cyclone track sinuosity and Coupled ENSO Index (CEI) between 1969-70 and 2007-08 seasons

Figure 5.11. Tropical cyclone track sinuosity and Coupled ENSO Index (CEI)
Further analysis in figure 5.12 shows a scatter diagram of monthly normalised sinuosity value plotted against monthly CEI. The correlation shows a negative relationship between the two variables with a $r^2 = 0.019$. There are fifteen (15) TC events with sinuosity values greater than 2.0 on the negative side of CEI compare to two in the positive side. All sinuosity values on the positive end of CEI values are not greater than $+3.7$ while sinuosity values of up to more than four correspond to CEI values up to $-4.64$. The highest sinuosity value is 4.21 with the CEI value of $-0.34$. 

Figure 5.12. Plot of tropical cyclone track sinuosity and Coupled ENSO Index (CEI).
5.5.2 Normalized TC track sinuosity and Sea Surface Temperature (Niño 3.4)

Time series of monthly Niño 3.4 plotted against monthly sinuosity in figure 5.13. shows positive values of Niño 3.4 were recorded during the early 1970s, the early and end of 1980s and 1990s, and beginning of the 2000s. Negative values were recorded during the early and mid 1970s, the mid 1980s and end of the 1990s and the 2000s.

Figure 5.13. Tropical cyclone track sinuosity and Niño 3.4 index over the 39 years.

Figure 5.14 shows a positive but less significant relationship between monthly Niño 3.4 and monthly normalized sinuosity values with $r^2 = 0.013$. A majority of TC events falls between negative and positive two of Niño 3.4 values. There are also events that occur above the +2 value of Niño 3.4 with the highest value of 3.8 compare with the lowest value of -2.14. The highest sinuosity value on the positive Niño 3.4 values is 4.21. Out of eighteen events with normalized sinuosity value greater than 2.0, fifteen of them are when Niño 3.4 is positive while only three events when Niño 3.4 is negative (figure 5.14).
5.5.3 Normalized TC track sinuosity and Southern Oscillation Index (SOI)

Times series of monthly SOI and monthly sinuosity in figure 5.15 shows positive SOI values during the early and end of 1970s, 1980s, 2000s and in mid 1990s. Negative SOI values were recorded during end of 1970s and beginning of 1980s, 1990s and 2000s. The highest SOI value is 3.14 recorded in November 1973 while the lowest (-3.33) recorded in February 1983 (figure 5.15).
The scatter diagram in figure 5.16 of monthly normalised sinuosity and SOI shows a negative and less significant relationship between sinuosity value and SOI with a $r^2 = 0.017$. The highest sinuosity anomaly values is 4.21 when SOI is negative (-0.84) while the lowest sinuosity anomaly is -1.01 when SOI is between –1.20 and 0.9. The pattern that emerges from the graph shows 2.6 as the threshold value of sinuosity where any value below this figure can happen on either side of SOI. Sinuosity value above 2.6 only occur when SOI is negative (figure 5.16).
### 5.5.4 Niño 3.4 and Southern Oscillation Index (SOI)

Figure 5.17 is a scatter diagram of the atmosphere (monthly SOI) along the y-axis plotted against the ocean (monthly SST (Niño 3.4)) along the x-axis. There is a strong relationship between the two indices with the $r^2$ value of 0.608. When Niño 3.4 is negative/positive, SOI is positive/negative. The higher/lower the Niño 3.4/SOI values, La Niña/El Niño event occurs within the Pacific region. This is similar to the results of previous studies.

Generally, when there is good coupling between the two indices (SOI and Niño 3.4), ENSO events should be represented by dots within the top left and bottom right corners of the graph (figure 5.17). However, what is depicted implies that when ocean and atmosphere are not in phase this provides lesser values for both indices which can
influence ENSO events with different magnitude and this can influence the TC activity as well. Therefore tropical cyclone track sinuosity cannot only be determined by the well-coupled phase of these two indices but also during periods when they are out of phase.

Figure 5.17. Plot of Niño 3.4 (SST) and Southern Oscillation Index (SOI).

\[
y = -0.857x - 0.238 \\
R^2 = 0.608
\]
The above diagram (figure 5.18) shows normalised monthly sinuosity values plotted against the different ENSO indices using the monthly values. There are ENSO events that are not well coupled meaning either it is a SOI (atmospheric) or Niño 3.4 (SST - oceanic) La Niña or El Niño events. There are also well coupled La Niña and El Niño events. The line in the middle of the diagram running from the top left corner to the bottom right corner, is the line of equal weighting or well coupling between the ENSO events that is either Niña / Niña 3.4 niño or Niño SOI/ Niña 3.4 niño. During La Niña events, there is strong correlation between SOI and Niño 3.4 and the sinuosity of tracks (sinuous or non sinuous) are constrained by the coupling of the two indices. However, during El Niño event, there is not dependency on coupling or sinuosity values are unconstrained by the coupling line and its spread is larger than those during La Niña event. The larger sinuosity values falls into the neutral phase leaning more towards El Niño phase.
5.6 Vanuatu case study

5.6.1 Annual temporal and spatial analysis

The Vanuatu AoR is within the RSMC Nadi responsibility and as a NMS, it is obliged to provide daily public, marine and aviation forecasts and TCs when an event occur within 12° S - 23° S and 160° E - 175° E. This role started since the establishment of VMS in 1985 and it compliments the responsibilities of the RSMC in Nadi in issuing TC advisories and information that is shared among the two organisations on a close working relationship. The role of VMS is to ensure that TC advisories and other weather related information provided by the RSMC are released through Vanuatu’s focal point (NMS) to local media outlets on a timely manner.

During the thirty nine year period (between 1969-70 and 2007-08 season), there were one hundred and fifty four (154) TCs that occurred within the Vanuatu AoR which is more than fifty two percent (52.2%) of the total TCs in the FMS AoR. From this total, forty nine (49) are in category one, seventy one (71), twenty four (24) and ten (10) are in category two, three and four respectively (table 5.15).

The number of TC in each sinuosity category occurring in the VMS AoR represents one to two thirds of TCs with that sinuosity value occurred in FMS AoR. More than half of those in categories two, three and four occurred in the VMS AoR. Category three has the highest percentage (68.6%) of TC within the VMS AoR while category one has the lowest percentage of 42.6% (figure 5.15).

<table>
<thead>
<tr>
<th>TC sinuosity category</th>
<th>Total number of TCs</th>
<th>% of TC in VMS to FMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category one</td>
<td>49</td>
<td>42.6</td>
</tr>
<tr>
<td>Category two</td>
<td>71</td>
<td>60.7</td>
</tr>
<tr>
<td>Category three</td>
<td>24</td>
<td>68.6</td>
</tr>
<tr>
<td>Category four</td>
<td>10</td>
<td>58.8</td>
</tr>
</tbody>
</table>

Table 5.15. Frequency of tropical cyclone in VMS AoR.
The monthly spread of TC tracks in sinuosity categories shows January to have forty four (44) TCs as the highest number of events follow by March, February and December with thirty two (32), thirty (30) and fifty (15) respectively. More than forty six percent (46.1%) of TCs in VMS AoR are in sinuosity category two followed with category one, three and four with more than thirty one (31.8%), fifteen (15.6%) and six (6.5%) percent respectively (table 5.16). Out of the nine TC occurring months, six of them (January, March, April, May, June, October, November and December) has majority of TCs with tracks in sinuosity category two, while February has more category one and October and November have majority of TCs in both sinuosity category one and two (figure 5.16).

<table>
<thead>
<tr>
<th>Months</th>
<th>Total TC Number</th>
<th>Category one</th>
<th>Category two</th>
<th>Category three</th>
<th>Category four</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TC No</td>
<td>%</td>
<td>TC No</td>
<td>%</td>
<td>TC No</td>
</tr>
<tr>
<td>January</td>
<td>44</td>
<td>28.6</td>
<td>12</td>
<td>27.3</td>
<td>19</td>
</tr>
<tr>
<td>February</td>
<td>30</td>
<td>19.5</td>
<td>14</td>
<td>46.7</td>
<td>9</td>
</tr>
<tr>
<td>March</td>
<td>32</td>
<td>20.8</td>
<td>9</td>
<td>28.1</td>
<td>17</td>
</tr>
<tr>
<td>April</td>
<td>12</td>
<td>7.8</td>
<td>4</td>
<td>33.3</td>
<td>8</td>
</tr>
<tr>
<td>May</td>
<td>7</td>
<td>4.5</td>
<td>2</td>
<td>28.6</td>
<td>4</td>
</tr>
<tr>
<td>June</td>
<td>1</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>October</td>
<td>3</td>
<td>1.9</td>
<td>1</td>
<td>33.3</td>
<td>1</td>
</tr>
<tr>
<td>November</td>
<td>10</td>
<td>6.5</td>
<td>4</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>December</td>
<td>15</td>
<td>9.7</td>
<td>3</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>100</td>
<td>49</td>
<td>31.8</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 5.16. Monthly summary of tropical cyclones in VMS AoR.

Figure 5.19 shows the spatial spread of the monthly sinuosity tracks of TCs in the VMS AoR. It identifies ahigh concentration of tracks in all sinuosity categories over its AoR during the month of January (figure 5.19 A) and March (figure 5.19C) while a lesser spread occurs during other months. Likewise more concentration of higher sinuosity categories (3 and 4) tracks during the first three months and most are concentrated on the western side of the AoR (figure 5.19 A,B and C).
A. VMS January TC tracks with different sinuosity tracks
B. VMS February TC tracks with different sinuosity tracks
C. VMS March TC tracks with different sinuosity tracks
D. VMS April TC tracks with different sinuosity tracks
E. VMS May TC tracks with different sinuosity tracks
F. VMS June TC tracks with different sinuosity tracks
Figure 5.19. Distribution of VMS tracks in sinuosity category in (A) January (B) February (C) March (D) April (E) May (F) June (G) October (H) November (I) December and (J) combined.

5.6.2 Decadal temporal and spatial analysis

There are fifty two (52) TC events which represents more than thirty three percent (33.8%) of the one hundred and fifty four (154) VMS TCs occurred during the 1980s ten year period followed with 1990s with more than twenty eight percent (28.6%). 1970s and 2000s have the least number of TCs between 1969-70 and 2007-08 season with
24.7% and 12.9% respectively (table 5.17). The highest TC mean sinuosity value is observed during the 1990s with 2.55 and the lowest is 1.29 during the 1980s ten years period (table 5.18).

<table>
<thead>
<tr>
<th>Decade</th>
<th>Count</th>
<th>%</th>
<th>Min</th>
<th>Max</th>
<th>Sum</th>
<th>Mean</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970-1979</td>
<td>38</td>
<td>24.7</td>
<td>1.01</td>
<td>2.79</td>
<td>49.93</td>
<td>1.32</td>
<td>0.37</td>
</tr>
<tr>
<td>1980-1989</td>
<td>52</td>
<td>33.8</td>
<td>1</td>
<td>3.72</td>
<td>67.07</td>
<td>1.29</td>
<td>0.43</td>
</tr>
<tr>
<td>1990-1999</td>
<td>44</td>
<td>28.6</td>
<td>1</td>
<td>52.55</td>
<td>112.2</td>
<td>2.55</td>
<td>7.65</td>
</tr>
<tr>
<td>2000-2008</td>
<td>20</td>
<td>12.9</td>
<td>1.03</td>
<td>2.68</td>
<td>29.05</td>
<td>1.45</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table 5.17. Statistics of VMS decadal tropical cyclone sinuosity values.

Out of the fifty two TCs in 1980-1989, twenty one of them are in sinuosity category one representing not only 40.4% of TCs during that decade but also more than forty two percent of TCs in that category. The 1970-79 period has the second largest number of TCs in this category with twenty six percent followed by 1990s with more than twenty four percent and 2000-2008 with more than six percent of TCs in sinuosity category one (table 5.18).
<table>
<thead>
<tr>
<th>Decade</th>
<th>Category one</th>
<th></th>
<th>Category two</th>
<th></th>
<th>Category three</th>
<th></th>
<th>Category four</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of decade total</td>
<td>% of cat total</td>
<td>% of decade total</td>
<td>% of cat total</td>
<td>% of decade total</td>
<td>% of cat total</td>
<td>% of decade total</td>
<td>% of cat total</td>
</tr>
<tr>
<td>1970-1979</td>
<td>13</td>
<td>34.2</td>
<td>26</td>
<td>18</td>
<td>47.4</td>
<td>25.4</td>
<td>4</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.7</td>
<td></td>
<td>3</td>
<td>7.9</td>
</tr>
<tr>
<td>1980-1989</td>
<td>21</td>
<td>40.4</td>
<td>42.9</td>
<td>22</td>
<td>42.3</td>
<td>31.0</td>
<td>7</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29.2</td>
<td></td>
<td>2</td>
<td>3.8</td>
</tr>
<tr>
<td>1990-1999</td>
<td>12</td>
<td>27.0</td>
<td>24.5</td>
<td>21</td>
<td>47.7</td>
<td>29.6</td>
<td>8</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33.3</td>
<td></td>
<td>3</td>
<td>6.8</td>
</tr>
<tr>
<td>2000-2008</td>
<td>3</td>
<td>15.0</td>
<td>6.1</td>
<td>10</td>
<td>50</td>
<td>14.1</td>
<td>5</td>
<td>25.0</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>20.8</td>
<td></td>
<td>2</td>
<td>10.0</td>
</tr>
<tr>
<td>Total</td>
<td>49</td>
<td>31.0</td>
<td>100</td>
<td>71</td>
<td>46.1</td>
<td>100</td>
<td>24</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td>100</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Table 5.18. VMS tropical cyclones in each decade since 1970

The highest number of TCs in sinuosity category two is during the 1980s with twenty two events representing thirty one percent (31%) of total TCs in this category. The 1990s, 1970s and 2000s recorded the least TC events in this sinuosity category with twenty one (29.6%), eighteen (25.4%) and ten (14.1%) respectively (table 5.18).

The 1990s period recoded eight TCs which is more than thirty three percent (33.3%) of total events in sinuosity category three while the 1970s recorded the lowest figure of TCs (four) which is 16.7% of total events. All decades have almost the equal number of TC events in sinuosity category four with two and three events, the latter occurred during the 1970s and 1990s periods while the former during the 1980s and 2000s (table 5.18). The decadal spatial spread of these tracks is to the west of VMS AoR than the easter side (figure 5.20). There are more highly sinuous tracks during the 1990s than other decades.
5.7 1990 to 2000 case study

This section will explore the spatial distribution of tropical cyclone track sinuosity during a ten year period starting from 1990 to 2000 to provide better understanding of how these different sinuosity categories are spatially distributed during a shorter period of time compared to the findings using a longer period found in section 5.2 and 5.3 in this chapter while at the same time provides a more spacious display of the tracks in the FMS AoR.
There are eighty two (82) tropical cyclones during 1990-2000 period with twenty eight (28) and thirty eight (38) in sinuosity category one and two while twelve (12) and four (4) systems falls in category three and four respectively (table 5.19). Figure 5.21 shows clearly that tracks in sinuosity category one (1-1.09) have an even distribution over the region.

However when specifically selected from their region of origin, there are nineteen (67.9%) tracks that originate in the west compared to nine (32.1%) in the east of South Pacific. This is the same for category two  which has twenty seven (71.1%) tracks that originated on the western side of the international dateline with eleven (28.8%) on the eastern side. The third sinuosity category has a similar distribution to that of the
previously two categories with ten (83.3%) occurrences in west compared with only two (16.7%) to the east. The final or fourth category shows three (75%) tracks out of four originated from the western region with only one (25%) on the eastern part of the South Pacific region (figure 5.21). It shows that a majority of tracks originates from the western part of the FMS AoR while only twenty eight percent (23 TCs) of tracks on the eastern side (table 5.19) during the 1990 – 2000 period.

<table>
<thead>
<tr>
<th>Sinuosity categories</th>
<th>TC west of 180°</th>
<th>TC east of 180°</th>
<th>TC total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>% W</td>
<td>Total</td>
</tr>
<tr>
<td>One</td>
<td>19</td>
<td>67.9</td>
<td>9</td>
</tr>
<tr>
<td>Two</td>
<td>27</td>
<td>71.1</td>
<td>11</td>
</tr>
<tr>
<td>Three</td>
<td>10</td>
<td>83.3</td>
<td>2</td>
</tr>
<tr>
<td>Four</td>
<td>3</td>
<td>75</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>59</strong></td>
<td><strong>23</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.19. The number of tracks in each sinuosity category during 1990-2000 year period.

In summary, the result in this chapter shows:

- a general increase in sinuosity with time,
- Sinuosity appears to be maximum during weak El Niño conditions and not during strong ones
- The sinuosity trends does not appear to be seasonally uniform (figure 5.10a)
- There are large decadal variations in sinuosity (table: 5.17)
Chapter: 6. DISCUSSION

6.1 Introduction

This chapter is divided into three sections with the first explaining the different categories or groupings of tropical cyclone track sinuosity; how they are grouped and assigning their different names. The second section summaries findings in chapter five and provides explanation on how sinuosity values change over time and space. The final part will present explanations on how the temporal and spatial sinuosity distributions are correlated to ENSO indices (CEI, SOI and Niño3.4) as climatic factors.

6.2 Naming of tropical cyclone track sinuosity categories

Tropical cyclones tracks have curvatures depending on the atmospheric, oceanic conditions and land features that are positioned on their migratory path. These factors combine to make tracks more sinuous, displaying a more complex pattern than a straight line. Here, tropical cyclone sinuosity values are classified into four discrete classes or categories (1.0-1.09, 1.10-1.49, 1.50-1.99 and ≥ 2). The breakpoints are chosen carefully, making sure that all sinuosity values calculated from the homogenized TC database are all included in one of these sinuosity categories. The four sinuosity categories provide a framework that can accommodate the different characteristics and behaviors of tracks, be they straight, slightly and highly curve and those that are have complex looping tracks and backtracked.

The first category includes all tracks that have sinuosity values of 1-1.09 which are straightened or straight thus; the curved distance of track is almost equal to its straight distance. For instance, a track with a curve distance of 1.00 and a straight distance of 1.00 will have a sinuosity value of one (1) and that falls in sinuosity category one. From that fact a suitable name that captures the characteristics of these tracks is ‘Straight Tracks’. This name (straight track) indicates a category which also contains straight
tracks with small curvatures allowing sinuosity values to reach 1.09. A good example of track from this category is tropical cyclone Priscilla during early 1970 (figure 5.2(A)) with a sinuosity value of 1.02 with its track located on the southwest of Fiji Islands.

The curvatures of tracks in sinuosity category two deviates from a straight line (straight track) and are slightly curve than straight with sinuosity values of 1.10-1.49. The common pattern of tracks in this category is mostly straight with some curvatures which the curve distance is just greater than the vector distance (distance between the start and finishing point). The suitable name for this category (two) capturing the characters especially the curvature of these tracks is ‘Slightly curved tracks’. A good example of a track in this category is tropical cyclone Vania, 1994 (figure 5.2(B)) with a sinuosity value of 1.36 displayed over the Vanuatu group.

As tracks becoming more sinuous, they display complex tracks including loop and relatively long and curvy sometimes backtracking and decaying relatively near the starting points. These tracks are included in the next two categories (three and four) that can be seen as the two groups of higher track sinuosity. The third category includes cyclones tracks with higher curvature deviation from their straight track than those in category one and two. The sinuosity value category for this group is within the range of 1.50 to 1.99. This category includes tracks that are either parabolic with a loop or a combination of curve and loops. The higher sinuosity value in this category shows that curve distance is almost double their vector distance. With these characteristics bestowed in these tracks, it is reasonable to name this category ‘Highly curved tracks’. An example of track from this category is tropical cyclone Abigail (1982) with sinuosity value of 1.85 occurred from northwest to southeast of New Caledonia with track combining of straight, curve and loop (figure 5.2C).

Cyclones tracks are not always straight and can follow any compass bearing during their lifespan making them hard to predict. Although more than eighty percent of tracks are in categories one and two following the normal general track direction of north northwest to southeast and are less sinuous, there are others that have complex shape involving
sharp bends, loops and often curving backtracks that are included in category four. The loops display by the tracks can be tight and are often associated with open curvature. Sinuosity category four comprises of these tracks which have more curvatures than those in the other categories (figure 5.2). The curve distance of these tracks are much greater (twice or greater) than their straight track distance compare to other categories. Since these tracks involve loops, curves in any compass direction, curving backtracks or combination of all the above characteristics of all tracks, this category is suitable to be name ‘Heavily sinuous track’. Tropical cyclone Betty occurred in 1985 is a good example of an event with sinuosity value in category four with a relatively long track involving a loop displayed between Vanuatu and Fiji (figure 5.2 D).

Two hundred and sixty seven out of two hundred and eighty four (267/284) tropical cyclones accounting for 94.4% of cyclone tracks, fall within the sinuosity range of one and two. The other seventeen (17), which constitute of 5.6% tracks, have sinuosity values greater than two (2). The highest track sinuosity value of 52.55 is for tropical cyclone Katrina in January 1998 since its track involves loops and more curvatures than those in categories one (1) to three (3).

The findings associated with the track shapes in this study were similar to Basher et al. (1990) who described cyclone behaviors, both in tracking and development and decay, as very erratic and difficult to predict beyond a day. Tracks may curl back upon themselves, but there are some characteristic patterns, which often take the cyclone in an eventual south easterly direction. These descriptions are now capture in the categorized four sinuosity groups and can always be refer to as track characters.

Even though these different sinuosity categories are chosen statistically, the groupings in figure 5.3 provides an indication of the differences exist in track sinuosity values both spatially and temporally. Therefore, the next section will provide some explanation on how the track sinuosity has changed over space and time.
6.3 Spatial distribution of sinuosity values

6.3.1 Introduction

The spatial and temporal distribution analysis of tropical cyclone track sinuosity is totally a new area of research and findings in chapter five presented interesting results. This section will therefore summarize the general spatial patterns in the South Pacific region using the four different sinuosity categories in previous pages. Typically, the general spatial distribution of all sinuosity values in the four categories depicts higher concentration of tracks to the western end compared to the eastern part of region (figure 5.3). Moreover, the more sinuous tracks originate farther west and south but still end in the west and the lower latitudes compared to other three lower sinuosity categories.

6.3.2 Category one (Straight tracks)

This category includes one hundred and fifteen tracks (115) or 40.5% tracks distributed (figure 5.3A) over both the west and east region of the FMS AoR during the thirty nine (39) year period. In addition to that, using the 180° meridian as a boundary dividing the east and the west reveals seventy nine (79) or 68.7% tracks in sinuosity category one (1) to originated in the western part of the South Pacific region compared to the thirty six (36) or 31.3% on the eastern side. Although this seen as evenly distributed on the map, the majority of tracks (68.7%) with sinuosity values (1-1.09) started in the western Pacific versus the eastern end (figure 6.1).
Figure 6.1. Distribution of tropical cyclone tracks in category one (A) west and (B) east of 180° (International Dateline).

The general orientation of tracks in sinuosity category one is from northwest to southeast (figure 5.3A) associated with a mean bearing of 149.3°. Only six events migrated to the southwest. There is a greater chance for tracks in this category to deviate from normal (northwest to southeast orientation) in the western part of the region compared to the eastern part. The normal northwest to southeast orientation of tracks established in this study is also supported by Terry (2007) who describe tropical cyclones as normally behaving by keeping tracks oriented generally northwest to southeast.

### 6.3.3 Category Two (Slightly curved tracks)

The sinuosity category two, also known as ‘slightly curved’, have tracks from both the western and eastern region of the South Pacific. However, a higher concentration originates from the western part, especially over Vanuatu and New Caledonia region. Out of the total one hundred and seventeen (117) tropical cyclones in this category, seventy nine events, or more than sixty seven percent, originates west of the 180° meridian. Thirty eight (or 32.5%) started in the eastern part of the region (figure 6.2). The TC numbers originating in the western region account for more than half of all events in this sinuosity category. This is clearly evident in figure 5.3(B).
The general orientation of the tracks during their lifespan in this category is south southeasterly as evident by the majority of the tracks with a mean bearing of 164.3°. However there are seven tracks that originated from the western side and deviate from normal track orientation, displaying a more southwestern turn than the normal southeasterly direction in their later TC stage. TC events that occurred in the eastern Pacific usually have their tracks oriented southwards or southeastwards, in line with the normal track orientation pattern.

6.3.4 Category three (Highly curved tracks)

There are twenty five (25) tracks (figure 6.3) that account for more than seventy one percent of TC events starting to the west of the region specifically over New Caledonia and Vanuatu group (figure 5.3C). The remaining ten events or 28.6% occur sparsely to the eastern part of the region; five of which are more spread from 170° E to 120° E. This indicates the vulnerable areas are to the west of the region where the majority of highly curved tracks can originate and maneuver during their lifespan.
The general trend of track orientation in this sinuosity category is to the south southeast with a mean bearing of 164.4°. The majority of tracks in this category are associated with curves and loops during the course of their migration and these characteristics are clearly evident in figure 5.3 (C). Despite being regarded as highly curved tracks with loops and curves, the tracks still maintain the southeasterly orientation, with only one deviating more to the southwest.

6.3.5 Category Four (Heavily sinuous tracks)

Sinuosity category four is comprised of tracks that are highly sinuous with sinuosity values greater than two (≥2); that is tracks have very sharp turns and loops with majority located in the west versus the east region as seen in figure 5.3(D). In figure 6.4, from the total seventeen (17) TCs, ten of them or 58.8% originate west of 180° meridian while seven (41.2%) in the eastern part. A greater concentration of these tracks occurred west, especially over Vanuatu, New Caledonia and towards the Coral Sea (figures 5.3D). The other 41.2% of tracks are sparsely spread between 180° E to 150° E. This again
reinforces the trend concentration of tracks including sinuous or heavily sinuous tracks located in the western versus eastern part of the region.

Figure 6.4. Distribution of tropical cyclone tracks in category four (A) west and (B) east of 180° (International Dateline).

The orientation of tracks in this category portrays a different picture from the first three categories where the general track orientations are usually from northwest to southeast direction. Since it includes tracks that are looping and zig-zagging, their general track alignment does not usually follow the normal track orientation of the northwest to southeast. The ending position of majority of tracks is in any direction, while although a few still maintain a south to southeasterly direction with an average bearing of 172.3° (figure 5.3D).

The general location of where TCs (with different sinuosity value) start and end is different for each event. However, the average starting position of tracks in sinuosity category four starts and finishes furthest west compared to the other three categories (figure 5.6). This finding is also similar to that of Hasting (1990). While he does not specify the sinuosity groupings, he describes the general distribution of cyclone origins to be increasing and spreading out across to 135° W longitude and falling in the latitude band of about 7° S to 20° S. They are also influenced by ENSO phases. During positive
SOI regimes the origins concentrate in the Coral Sea, with few beyond 180° W, and end in the latitude band of 10° S to 23° S. This is further supported by Revell and Goulter (1986) that cyclone starting positions and tracks shift to the north and east during periods when the SOI is negative. In both ENSO phase the tracks cover further southern latitude range of seven degrees.

The overall conclusion drawn from the spatial pattern is that the majority of tropical cyclones, despite their track sinuosity values, occurred in the western portion of the South Pacific region. Out of the two hundred and eighty four (284) tracks, one hundred and ninety three (193) tracks or 68.0% originate from the west whilst ninety one (91) events or 32.0% originate in the eastern region of the Pacific. This spatial distribution pattern in categories one to four constitutes a western concentration of tracks even going from the less to more sinuous tracks as seen in figure 5.3.

6.4 Tropical cyclone track sinuosity temporal change

This section summarizes findings in chapter five and provides explanations to the temporal distribution of tropical cyclone track sinuosity values using the categories mentioned in section 6.1. Temporal distribution is how a TC sinuosity value changes with time.

6.4.1 General pattern

The general temporal pattern emerging from the analysis chapter shows more than twenty four percent (24.6%) of TC tracks occurred during the month of January, the most TC events to occur during any month. A majority of TCs with sinuosity category one and four occur during the month of February while category two and three mainly in January. Thus TCs that occur during January will have more than forty four percent
chance of having a sinuosity in category two (1.10-1.49) and a seventeen percent chance of having a sinuosity values in category three (1.50-1.99). Events that occur in February have more than forty four and five percent likelihood of having sinuosity values in categories one (1.00-1.09) and four (≥2.00) respectively (table 5.11). These percentages represent the highest chances of getting a TC event within those sinuosity categories during the four months.

Annually, TCs events with sinuosity category one increased until the middle of 1980s then reduce in the later years, with a trend of r² = 0.105. There is also a declining trend (r² = 0.006) in time series of TC frequency with sinuosity between 1.10-1.49, with peak frequency during the early 1980s and 1990s. However there is a positive trend in TC frequency in sinuosity category three, with r² = 0.073. TC frequency remains the same for TCs in sinuosity category four (r² = 0.001) (figure 5.8).

During the four decades between 1970 and 2008, there is a rise in TC frequency with sinuosity values in category two between 1980 and 1989 that declines thereafter. Category one has a declining trend until 2008. Category three increases during the first three decades. TC numbers in sinuosity category four remain the same during the four decades (figure 5.9 and table 5.14). The trends may not provide a picture of the reality since there is only four reference points to produce the trend. However, the Z-score test (figure 5.10) reveals a positive trend in TC numbers with sinuosity category three compared to other categories where there is a declining trend for other sinuosity categories, with more heavily sinuous tracks having occurred in the past four decades.

The findings of this study, especially the temporal sinuosity distribution patterns are similar to the TC pattern established by Terry and Gienko (2011) who reported extended periods lasting several years when sinuosity was notably higher (e.g. 1981-83 and lower (1999 - 2002) than normal. They further describe a decadal pattern in sinuosity index suggests a weak upward tendency over the past four decades. Figure 5.9 shows a similar trend, where during the past four decades there is no significant change to TC numbers in highly sinuous category four.
6.4.2 Vanuatu case study

The Vanuatu case study reaffirms the similar spatial and temporal distribution of TC sinuosity to that of FMS AoR. The highest TC frequency occurs during the month of February for category one and January for the other three sinuosity categories. There are more TC events in the 1980s than other decades. More than seventy percent of TC events occurring in VMS AoR are in sinuosity category one (table 5.18). Spatially, the concentration of sinuous tracks (sinuosity three and four) is located to the west of the AoR while the less sinuous spread across the AoR (figure 5.20).

6.4.3 1990-2000 case study

The ten year period between 1990-2000 displays a spatial and temporal sinuosity trend similar to that which occurs in FMS and VMS AoR, where a higher concentration of tracks is on the western versus the eastern part of the region and especially over the area between Vanuatu, New Caledonia and the Coral Sea region (figure 5.21 & table 5.19).

6.4.4 Normalized TC track sinuosity and ENSO Index

The three main ENSO indices used in this study analyzed in chapter five are the CEI, SOI and the Niño 3.4 (SST). The finding using simple correlation techniques shows a weak negative relationship ($r^2 = 0.019$) between the TC sinuosity values and CEI (figure 5.12). A similar relationship ($r^2 = 0.017$) exist between sinuosity and SOI (figure 5.16). Both figures reveal that any TC with sinuosity values greater than two are likely to occur when CEI or SOI is negative. However there is a weak positive relationship ($r^2 = 0.013$) between sinuosity and Niño 3.4 (figure 5.14) showing values of sinuosity greater than two only happen when Niño 3.4 is positive. These findings indicate that during El Niño events, TCs are more likely to be more sinuous when CEI and SOI are negative or when Niño 3.4 is positive. The correlation between the three indices and sinuosity confirms
CEI has the highest correlation value and is the best index to use in this research especially with TC sinuosity.

6.4.5 Explanation of spatial and temporal sinuosity patterns

The correlation established between the three climate predictors provides insights on how they influence the tropical cyclone track characteristics. Though there are only weak positive and negative relationships that exist between ENSO indices and track sinuosity, to an extent they influence the migration pattern and the general morphology of TC tracks. This fact is supported by Basher and Zheng (1994) who confirm that climatic factors associated with the distribution of tropical cyclone incidents are related to the Southern Oscillation Index (SOI) and the Sea Surface Temperatures (SST). The relationship between the three main ENSO indices and TC climatology in the South Pacific region is further supported by Kuleshov (2009), who suggest that larger environmental conditions such as the Walker circulation changes during different ENSO phases (El Niño and La Niña) influence climatic conditions in the Pacific region favoring cyclogenesis areas to shift and affecting the climatology of TC in the South Pacific region. However, how these ENSO indicators influence the surrounding environmental is outside the scope of this research.

Whether it is a seasonal, annual or decadal change, the temporal and spatial changes in track sinuosity, are influenced by the spatiotemporal characteristics of ENSO, which sometimes is not well coupled between the ocean and atmosphere and as a result produces different kinds of events. This is described by Maue (2010) as ENSO undergoing variations such as the canonical El Niño (cold tongue - CT) and El Niño modoki events on decadal scale. Therefore the small changes in the strength and type of ENSO phenomenon can also influence the sinuosity values to a certain extent.

The other factor that contributes to the different TC track sinuosity is the position of the SPCZ which controls the environmental conditions and dictates tracks sinuosity spatial
and temporal patterns found in chapter five. Positioning of the SPCZ as a main climate driver in the South Pacific region is influenced by the ENSO phases further explained in the literature review (chapter four). Studies have found SPCZ to influence TC genesis in the South Pacific region (Vincent et al., 2009) and the influence is in three phases of SPCZ location. One and two is three degrees (3°) north and south of its normal position while the third location displays peculiar behavior where the SPCZ largely departs from its climatological position and is zonally oriented. The third displacement of SPCZ occurs only during extreme El Niño years and is zonally oriented around 6° S (figure 4.16). Refer to 4.17 and 4.18

This study concludes that the possible scenario for straight tracks is when SPCZ lies in its normal position (climatology) that is from Solomon Islands to Samoa, with the tracks usually following its orientation since it is an area of embedded low pressure that dictates TC tracks to be straight. Therefore TCs that form during this period where SPCZ is in this location will have straight tracks with a northwest to southeast migration path. This scenario is associated with TC tracks in sinuosity category one and two in this study, with mean track bearing of between 149.3° and 164.3°.

The second possible scenario is during periods when SPCZ is southwest from its normal position. During La Niña events, the SPCZ southeastern end slides over Vanuatu and further south (an example is SPCZ location during the 1999/2000 La Niña event). During such circumstances, TCs follow the curved alignment of the SPCZ, so tracks become highly curved and move southwest and can be related to sinuosity category three with an average bearing of 164.4° (Table 5.10).

The third possible scenario influencing track sinuosity is during when the SPCZ location is situated further north from its normal position than during El Niño events, a position is almost parallel to the equator but lying around 6° south. During such periods, the SSTs along the Equatorial Pacific are much warmer thus influencing TCs to maneuver along that area and even towards western Pacific region where warmer SSTs anomalies do exist, causing the track to be more sinuous. This is how such shifts in SPCZ location in
extreme events can influence TC tracks in sinuosity category four (highly sinuous tracks). The reason why TCs are more sinuous during El Niño years is because during warm ENSO events (El Niño), the equatorial Pacific region is warmer therefore TCs form closer to the equator and further towards the eastern Pacific. Terry and Gienko (2010) describe such shifts are related to El Niño, associated them with equatorial (northward) shift in average cyclogenesis location. In contrast, cool phases of ENSO (La Niña) tend to give more southerly cyclone origins. They cautioned that the eastward or westward shift in mean cyclogenesis location is not clearly linked with the swings with the SOI. The findings of this study were also similar to that of Basher and Zheng (1994), which suggest that the systematic shifts of the cyclone incidence are similar to those of the SPCZ where there is availability of moisture that favors TC occurrence.

ENSO influence on the shift of SPCZ location controls the cyclogenesis and pattern of TC in the South Pacific region, whereas the SSTs are a precondition that plays a major role in determining the climate conditions during those periods. The warmer SSTs change location during the course of ENSO events shifting further west/east during La Niña/El Niño events. This factor coupled with the influence of different ENSO phases determines the location of cyclogenesis area. As Kuleshov (2009) stated that during El Niño events, the above climatology of tropical cyclogenesis is observed over the eastern part of the basin east of dateline with highest frequency of 0.6 over Vanuatu and Coral sea area (figure 4.21). During La Niña episodes, TC genesis occurs further away from the equator (below 10°) and is displaced to the western part of the basin closer to Australia, with a higher average (1.0 TC) over the west of Vanuatu and New Caledonia area (figure 4.22). This also confirms that SST over the Coral Sea region does have influence on TC track and the SPCZ location.

How often the SPCZ moves monthly, annually and on a decadal time frame coupled with its behavior during different ENSO events over time in this region also contributes to the frequency and behavior of TC over time. Widlansky et al., (2010) stated that SPCZ’s spatial orientation and its longer term variability are influenced by the El Niño-Southern Oscillation (ENSO), or alternatively, the changing back-ground SST associated
with different phases of ENSO. This is also confirmed by Vincent et al., (2009) that cyclogenesis interannual variability in the South Pacific region is shown to follow SPCZ movement in its north-south displacement and preferentially occur within 10° south of the SPCZ location (figure 4.18).

The majority of TCs that occurred east of the dateline are those with sinuosity in category one and are likely to occur when the SPCZ moves further north during El Niño years, supported by Vincent et al., (2009). Often such conditions can also influence TCs with highly sinuous tracks, as prevailing conditions allows a TC event to maneuver from east to west (figure 5.4(D)).

This study also concluded that during January and February, when a majority of TCs tracks with low and high sinuosity values occurs when SPCZ is most active over the South Pacific region, especially over its climatology area or sometimes displaced below its normal position. Therefore the SST over the Coral Sea area and the monthly shift in SPCZ location do play an important role in determining the sinuosity values of a TC tracks, accounting for sixty eight percent (68.0%) of TCs occurring to the west of dateline where majority on this side are highly sinuous compared to those on the eastern side. That relationship is outside the scope of this research. However, it will be interesting to find out if such a relationship exists between SSTs around the Coral Sea region and the shift in SPCZ and its influence in the TC track sinuosity.

There are other factors that influence the steering of TCs in the South Pacific region besides the influence of large scale circulation factors such as ENSO. This includes factors such as, the topographic (terrain), high pressure cells and the steering flow which also contributes to the track shape of a TC event but are outside the scope of this research.

More than sixty percent of all tracks (percentage is different for each sinuosity category. Refer to table 6.1) in all sinuosity categories occur west of dateline and geographically. A majority of big islands are also to this side of the dateline compared to the east. To the
west there are Australia, New Zealand, PNG, Solomon Islands, New Caledonia, Vanuatu and Fiji forming the main island nations. Should Australia and New Zealand be excluded, the bigger islands nations in the Pacific still remain in the western region and account for more than ninety six percent (96.1%) of total land area in the region (table 2.1). Coupled with the active convergence plate boundary location on this side of the Pacific, islands are more mountainous with more steep terrain and higher landscapes compared to those of the eastern South Pacific. Therefore whenever a TC event transverse the islands in the western Pacific, the tracks can be deflected in some way. The degree of track deflection also depends on the speed of TC, especially on its contact with landmasses. This is supported by Jian and Wu (2005), who suggest that landmass and terrain plays an important role in TC deflection. Fast moving storms have less time to deflect while slow moving TCs can deflect and can have loops. This idea may be true in some ways but figure 5.3 shows majority of tracks that have loops and more deflections occur in the open sea with the Australian landmass to the west. Therefore the influence of landmass may not be too relevant in this regards, as landmass is very small. Thus, the atmospheric factors may play the primary role in determining the track characteristics.

The high pressure cells normally migrate to the north during the dry season (May to October) and further south during wet season (November to April), and this seasonal pattern plays an important part in steering a TC event. When a high pressure cell during the wet season is dominant over the Pacific with ridge extending further north, it keeps TCs well established in the trade wind belt and keeps the track on a northwest to southeast direction. This is supported by Terry (2007) who further stated that an advancing trough of low pressure can cause a storm to recurve.

The other reason for the different track shapes found in this study is the steering flows that play important roles in steering of a TC event. The steering flow of tropical cyclone is from 700hPa to 500 hPa and wind direction from this level changes during different ENSO phases. This is similar to what Chand and Walsh (2009) suggested that during El Niño event, the 700 hPa wind field is eastward and later becomes northwesterly steering
TCs southeastward into northern part of Fiji islands and the Tonga region. This explains why TCs form east of the dateline and migrate southeastward east of dateline. In contrast, during neutral events there is slightly southwestward displacement of northwesterly flow that steers TCs developing east of dateline to slightly eastward to the south of Samoa. During La Niña years, the steering flows are displaced further poleward with initial flows from eastward between 10° S and 15° S, steering TCs formed around 15° S and 170° E over the Fiji islands and Tonga.

### 6.4.6 Track sinuosity and other track elements

This study also identified relationships between sinuosity and various elements of tracks that are of interest but do not form a major part of this research. However, they do provide clear perception into areas of interest in this field that can be further studied. This study identified that TC tracks with higher sinuosity values have a mean starting position further west (175.5° E and 15.8° S) while lower track sinuosity have a mean starting location of between 174.9° E and 14.9° S (refer to table 5.10). However, there is no correlation between mean starting latitude and longitude of TC events with sinuosity (Figure A.4 & 7.5) using simple correlation analysis with $r^2 = 0.001$ and $r^2 = 0.002$ respectively. The position of cyclogenesis locations are greatly influence by the ENSO indices which this research earlier established and further supported by Terry and Gienko (2010) who also identified that the relationship using Multivariate ENSO Index (MEI) is significant between cyclogenesis latitude and SOI and (MEI).

There are weak negative relationships between sinuosity and straight track distance ($r^2 = 0.031$) shown in Figure A.6. This indicates that the shorter a straight track distance, there is possibility of higher sinuosity value. This is further highlighted when mean straight track length is calculated (table 5.10) and mean sinuosity value increase as straight track length increase to 2565.5km then decrease while sinuosity value still maintain an increasing trend. This reflects what happens in the real world where a TC event can loop and curve in a small global coverage area with a short straight track length but has a high
sinuosity. The mean global coverage area increase for sinuosity category one and two but decreases for the higher two sinuosity categories ($r^2 = 0.001$).

There is also no relationship between sinuosity and mean wind speed ($r^2 = 0.001$). Interestingly, sinuosity is higher when mean wind speed is less than fifty knots (Figure A.10). This indicates that systems with less wind speed can be more sinuous than those that are destructive. This also emphasis the fact established by earlier research (Jian and Wu, 2005) that TCs with slower travelling speed can deflect or loop compared to those travelling at higher speed. Therefore this can be important in predicting the extent of damage caused by different category TC events.

A positive weak correlation exists between track bearing and sinuosity ($r^2 = 0.046$) which implies that the higher the track bearing value a track has the higher the mean sinuosity values. However, the concentration of higher sinuosity values is between 100° and 200° bearing with a mean track bearing of about 174.0° (Figure A.8). This proves that TC tracks with higher sinuosity do have higher track bearing but a lower mean global coverage area and shorter mean track length to some extent. Such relationships established in this research need to be further investigated to identify the dynamics and their degree of influence on track sinuosity.

So in a changing climate, how will track sinuosity values change in the South Pacific region? Will they become more or less sinuous and what are the implications in the region? This is again outside of the scope of this study but it is appropriate to provide a generalization on the possible scenarios with regards to the relationships established in this research and what other researchers suggest on the possible climate future of the Pacific island nations. A recent report in the Pacific on climate change known as the Pacific Climate Change Science Program (PCCSP) establishing climate science and future for Pacific suggests that TC numbers will decline in the southwest Pacific Ocean Basin. This is supported by Terry and Gienko (2010) who report that there is no linear trend in cyclogenesis origins, cyclone duration, track length over the last four decades which implies no evidence of climate change forcing of these storm characteristics over
recent historical time. However, surface temperature, sea surface temperature (SST) and intensity and frequency of extreme heat are projected to increase with little change to drought events. The decline in TC numbers means lesser tracks and there is not clear indication of whether track will become more or less sinuous. Findings from this study identifies that there are higher probability (41.2%) of tracks to be in category two (1.10 – 1.49) followed with 40.5% in category one (1.00 - 1.09), 12.3% in category three (1.50 – 1.99) and 6.0% in category four (≥2.0). With the SST, surface temperature and extreme heat projected to increase; this can provide TCs, ideal conditions to survive longer and migrate to places where positive SST anomalies may exist. This may indicate that tracks will become more sinuous. This suggestion is inconsistence with what Terry and Gienko (2011), who identified a lack of a statistically significant trend in track sinuosity that is probably more realistic. This would suggest that this feature of cyclone behavior remains unaffected by recent climate change. With the sea level rise currently experienced in the Pacific region, there is possibility that storm surge associated with TCs may inundate coastal areas further inland than before putting biodiversity and people’s lives at risk. The little change to drought events projected by the PCCSP report means the frequency of ENSO extreme events will remain the same with almost every three years of occurrence and the associated visitation of TCs to the eastern Pacific continuing to be an issue. As the frequency of ENSO events remains the same and with the current two to three years frequency of an ENSO event, there is a possibility that for tropical cyclone tracks will be more sinuous in the future. These are only suggestions given the relationships that exist between the different components that influence TC genesis and its characteristics. However this has to be carefully looked at in a changing Pacific climate in future studies.

To conclude, there are temporal and spatial sinuosity patterns that exist in the South Pacific region. A majority of less to heavily sinuous (category one to four) tracks occurred during January and February with declining trends over the years for the one and two, increasing trend for category three, and a slight increasing trend in category four. A majority (68.0%) of all tracks are located in the western part of the South Pacific region over the Coral Sea, Vanuatu and New Caledonia, while fewer (32.0%) occurred
to the eastern side of the dateline. The tracks are less/heavily sinuous during La Niña/ El Niño event. These findings shows that temporal and spatial distribution patterns of track sinuosity values exists; are controlled by climate factors like large circulations (ENSO), and are influenced by landmass, high pressure systems and winds in the 500-700 hPa over the region of the South Pacific. There is need for further investigation into the physical basis for the fluctuation in TC sinuosity which is not clearly known and beyond the scope of this paper.

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</table>


6.5 Reliability of results

Though this is the first study of its kind to be done in the region using scientifically established ENSO indices, the findings of this study can be considered reliable. The results are consistent with findings from recent research of TC in the South Pacific region especially those of Terry and Gienko (2010). However there is still need for further research to identify climate and physical drivers that determines the dynamics of TC track sinuosity and other characteristics of TC tracks especially in this region where landmasses are small yet highly sinuous TC tracks exist.

The results obtained in this research provide a better understanding of both the spatial and temporal differences in track sinuosity and can form the basis of including cyclone
track characteristics and behaviors in tropical cyclone advisory bulletins where currently neither are incorporated. What this research provides is not only an additional information to be use in cyclone analysis but a breakthrough for additional knowledge on track sinuosity that future research can be based on to make tropical cyclone track sinuosity predictions possible.

This research has shed some light on the quantitative evaluation of the tropical cyclone track sinuosity analysis and should benefit tropical cyclone seasonal forecast. It can be used in the existing climate models to give possible scenarios for the future. If such analysis is operational at the NMS in the South Pacific region, there is some hope that it would provide valuable information, not only for tropical cyclone researchers and forecasters, but to people living in tropical cyclone prone areas, by providing vital piece of additional information to the normal TC bulletin. Note that in this research, more emphasis is put on the spatial and temporal differences in the different sinuosity categories, yet there may be other influential factors that may play important roles in determining these differences.

In addition to the inclusion of track sinuosity in seasonal forecasting of tropical cyclones, this information can also be used in its damage assessment. The level of impact can be different for each cyclone track and the sinuosity provides vital information on this. In relation to this finding, a possible research area can be to establish the relationship between track sinuosity, the period the system exists, and it’s level of impact on a community. The logic is the more sinuous a track is, the greater the damage. With this, the level of damage can be determined by someone sitting in the office by knowing the track sinuosity values. This, however, does not mean it will replace the aftermath visitation and damage assessment of responsible government agencies, but it provides a quicker way to determine the level of impact so aid distribution can be swiftly dispatched to reach affected areas in time compare to the weeks after visitation reports.
On the same note, the temporal and spatial track sinuosity patterns can be used in tropical cyclone mitigation activities. Given the spatial and temporal differences, tropical cyclone awareness can include this track sinuosity information to communities prior to the commencement of each season. This will empower the local people and whole community at large about the possibilities of track behavior and characters in a particular season. With the inclusion of this information to the communities, people become aware about the level of impact of any cyclone happening in a particular season therefore will enable them to become proactive and not reactive as the current tropical cyclone warning bulletins encourage. The usage of this information will provide a better understanding of the character and behavior of tropical cyclones to people and will enable better preparation and mitigation to minimize the number of deaths this natural phenomenon may cause annually in the South Pacific region.

This study further illustrates that countries in the South Pacific region will remain vulnerable to irregular tropical cyclone behavior in the future. As people become more aware of the behavior and characters of tropical cyclone, ways of living will be shaped and changed around these beliefs encouraging a more sustainable livelihood. This will further help the government organizations in agricultural, marine and other productive sectors in each country to formulate plans and policies on how to become more productive and in the long run, individual countries will become more productive economically with minimal TC impact.
Chapter: 7. CONCLUSION

7.1 Summary of results

Understanding the characteristics and behavior of tropical cyclones in the South Pacific region is paramount as this natural phenomenon annually affects the developing island nations both economically and environmentally. The understanding of tropical cyclone track sinuosity becomes an important part of the issues to tackled related tropical cyclone problems and therefore, this study focuses on using a thirty nine (39) year tropical cyclone dataset provided by both the RSMC in Nadi (Fiji) and Tropical Cyclone Warning Center (TCWC) in Wellington (New Zealand) that includes all TCs for the South Pacific region.

The main objective of this research is to compile and verify a complete tropical cyclone dataset for the whole South Pacific region especially those occurring within the FMS AoR. With the collective approach of utilizing tropical cyclone data from TCWC and RSMC, a total of 346 tropical cyclone found to have occurred in this region for the past 39 years of which 284 (82.1%) began or have migrated into the FMS AoR. With the 284 TCs, the sinuosity values of each track are calculated which is basically the differences in the curve and straight distance of a particular tropical cyclone track and is achieved using the Haversine formula. The sinuosity values of these 284 tropical cyclones are formulated and categorized into four different sinuosity categories. The four categories include firstly ‘straight track’ (1-1.09), secondly ‘slightly curved’ (1.10-1.49), next is ‘highly curved’ (1.50-1.99) and finally ‘heavily sinuous’ (≥2.0) track. The sinuosity categories had 115 (40.5%), 117 (41.2%), 35 (12.3%) and 17 (6.0%) tracks respectively, ranging from categories one to four. The number of tropical cyclone tracks in each category provides an indication of the differences that exist not only in each category but also in temporal and spatial perspectives.
This study also seeks to examine the temporal and spatial patterns in track sinuosity categories and has reached the conclusion that there is temporal and spatial difference in existence between the four sinuosity categories.

Temporally, a majority of these tracks in sinuosity category one are found to occur in the month of February, category two and three takes place in January, and category four forms in February. This confirms that a majority of less or highly sinuous tracks occur between January to February each year. Comparing the pattern of which less sinuous track categories one and two behave annually versus occurrence during the last four decades have seen maximum number of tracks occurred during 1970s and 1980s. However, there was a decline in year 2000 with a shift to more increased frequency during that period compared to the past three decades for the sinuous track categories three and four.

The spatial distribution of the four sinuosity categories are shown to have differences across the South Pacific region with more than fifty percent of tracks in each sinuosity category located to the western part compared to the eastern part of the Pacific which accounts for between twenty eight (28%) and forty one percent (41%). Overall, there are sixty eight percent (68%) of tracks that have started in the western part, of the FMS AoR compared to the eastern part with thirty two percent (32%) (table 6.1). These findings are further supported using the case study of tracks in Vanuatu AoR and during the years 1990-2000 where similar patterns were identified.

Correlation analyses using the different ENSO indices and sinuosity have shown weak relationships. During an El Niño event, there is higher likelihood of tracks to be more sinuous, but the degree of sinuosity does not depend on coupling of SOI and SST. On the contrary, during a La Niña event, sinuosity depends on coupling of SOI and SST. Therefore, less sinuous tracks are likely to occur.

While it is beyond the scope of this study to establish the dynamics behind the spatial and temporal relationship and distributions of the four sinuosity categories, there are
reasons why these patterns occurred and that can be attributed to the large scale climatic
circulations that exist in the South Pacific region that recent studies labeled as the
‘principal controls’. These principal controls emphasized by Basher and Zheng (1994)
are based on the general idea that among the various climatological conditions necessary
to cyclone formation, there will be at least one that is less satisfied and therefore more
influential in determining cyclone incidences which are the SST and SOI, that are
closely associated with ENSO. These climatic conditions include the SPCZ, ITCZ, sub
tropical highs, the steering flows of 500 and 700hPa and landmass which are climatic
drivers and physical factors affecting the track sinuosity. However, there is a need for
more in-depth research to determine their degree of influence in establishing the track
sinuosity. It is the hope of this study that these findings can be practically used in all
NMS throughout the Pacific.

7.2 Recommendations for future research

There are a number of areas identified in this study that can be further developed via in-
depth research in order to provide better understanding of the dynamics behind the
spatial and temporal sinuosity distribution. The areas that can be further explored include
the relationships between sinuosity and ENSO indices where a single index can be
devised to capture the spatial and temporal patterns that were identified in this study.
Such an index could be used to provide forecast for track sinuosity included in the
annual TC seasonal forecast.

While TC data is provided by the RSMC and TCWC, there were differences that are
inevitable between the two databases. This requires time and effort to ensure that these
data have minimum or no associated errors and are of quality. To overcome the
discrepancies, it is recommended that future research use TC database developed by
Diamond et al., (2010).

Some of the difficulties faced during the course of study have identified that RSMC
(Nadi) can work closely with NMS to overcome some areas including the different
classification systems used in tropical cyclone monitoring, format and archiving system of data storage that has to be consistent throughout the region or even globally to enable efficiency without any hindrance to data processing. Some of the areas that need further improvement are discussed below.

1. Since there were differences in classifications used for tropical cyclone monitoring around the world, there is a need for more collaboration between the NMS in the Pacific region to apply the same standard or classification to record and archive tropical cyclone data to promote consistency across the region. In order to have a consistent monitoring standard for the FMS AoR, it is recommended that an agreement be formulated to ensure there are no TC monitoring discrepancies. Thus, TCWC adopt the RSMC TC monitoring procedures when taking over responsibilities of FMS, the purpose being to oversee the regional monitoring of TC in FMS AoR and ensure continuous service delivery when the NMS not being able to fulfill its functions due to different circumstances.

2. During the collection of TC data, there are some discrepancies when it comes to naming a TC event. Some systems that have been named by RSMC are not named by TCWC. There were also some cases where post analysis showed that the systems needed to be given a name but was not named during the time of event and post analysis will improve tropical cyclone data if it be allowed. Therefore, people who are responsible for climate data must, to an extent, have some knowledge of the different TC classification systems which is mandatory for accurate interpretation or comparison of tropical cyclone forecasts and statistics prepared by various national meteorological services. Moreover, adoption of a universal system of tropical cyclone classification would eliminate the current confusion.

3. The other difficulty that often hindered the progress of this study is the format in which the tropical cyclone data are stored. There are different formats used in
storing of tropical cyclone data throughout different years, therefore causing difficulties when importing data from notepad to excel. It has been experienced often that importation is associated with errors. These errors are often linked with time and dates (table 7.1) of occurrences of systems and there is need for this to be consistent. Therefore, to make archiving and importation of tropical cyclone data easy to manage and workable, a set standard format of data storage is required.

<table>
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Table 7.1. An example of date in storage format for tropical cyclone data

4. Data incompleteness is also be a problem and prolongs the analysis part of this research. Missing data such as wind speed, pressure, position (latitude and longitude) added to the data discrepancies which in this research do not matter since these data are complemented by using those provided by TCWC in New Zealand. The missing elements are for the tropical depression stage of a system and while are not relevant to this study, can be useful to other research. Therefore more consistency in data archive format is required to have a complete set of tropical cyclone data.
5. The difference between ex-tropical cyclones and frontal systems has to be clearly stated in cyclone data or records in order to analyze only tropical cyclone stages exclusive of when it becomes a frontal system where few in this study is inclusive of frontal system producing tracks to the higher latitude which will raise some questions.

6. Meteorology is a field that GIS has not explored because it has its own software and systems with already well established models and analytical techniques. The GIS applications are not widely used in this field. However, it has become a useful tool that can provide spatial and temporal distribution and many other techniques of analysis for meteorological variables like track sinuosity. It also provides good results for research discussions and can be applicable to other meteorological variables as well. The usage of GIS in mapping of track sinuosity not only provides display of tracks but it gives options for researches to use the analytical tools and techniques and other applications of GIS that can bring results from input data.

The above recommendations are not only beneficial to tropical cyclone related research but since the use of ArcGIS is across different sectors; it can be applicable to other fields. The consistency in data storage format and data completeness is of significant importance to any study. It is critical to have these research components completed and in workable format in order to assist in future research by allowing less time for data sorting and verification. More time can be spent on analyzing and discussions of data to enable researchers’ makes new findings and push back the frontiers of knowledge.
REFERENCES


APPENDIX

A. Sinuosity category one monthly TC changes

B. Sinuosity category two monthly TC changes

C. Sinuosity category three monthly TC changes

D. Sinuosity category four monthly TC changes

Figure A.1. Z-score test for changes in monthly TC frequency in each sinuosity category.
A. Sinuosity category one annual TC changes

B. Sinuosity category two annual TC changes

C. Sinuosity category three annual TC changes

D. Sinuosity category four annual TC changes

Figure A.2. Annual Z-score test for sinuosity category (A) one (B) two (C) three and (D) four.
A. Sinuosity category one decadal TC changes

B. Sinuosity category two decadal TC changes

C. Sinuosity category three decadal TC changes

D. Sinuosity category four decadal TC changes

Figure A.3. Decadal Z-score test for sinuosity category (A) one (B) two (C) three and (D) four.
Figure A.4. Tropical cyclone track sinuosity *versus* longitude of cyclogenesis position. Note: positions east of 180° are given longitude values >180°, e.g. 170°W is plotted as 190°E.

Figure A.5. Tropical cyclone track sinuosity *versus* latitude of cyclogenesis position.
Figure A.6. Tropical cyclone straight track distance versus sinuosity values.

Figure A.7. Global area cover by tropical cyclone versus sinuosity values.
Figure A.8. Tropical cyclone track bearing versus sinuosity values

Figure A.9. Tropical cyclone mean central pressure versus sinuosity values
Figure A.10. Tropical cyclone mean wind speed *versus* sinuosity values