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Statistical Climatology of Landfalling Tropical Cyclones in Australia Over 61 Years (1946-2006)

Kamal K Saha and Saleh A Wasimi*

CQ University, Bruce Highway, Rockhampton, Queensland 4702, Australia

Abstract

Tropical Cyclones (TCs) in the Australian basin have relatively more erratic pathways than other parts of the world. About half the TCs generated in the basin make landfall, but the location of cyclogenesis appears to have a direct bearing on landfall outcome. As the human and economic toll of landfalling TCs are far more significant than the non-landfalling ones, this paper attempts to identify the distinguishing features that differentiate between the two and, develops a decision tree model that can predict whether a TC is likely or unlikely to make landfall. Furthermore, this study captures the statistical properties of landfalling tropical cyclones in the context of Australia, which are described in the framework of sub-basin characteristics, temporal and spatial movements from genesis to lysis, and descriptive parameters.

Keywords: Tropical Cyclones; Australian Basin; Landfall; Statistical Analysis

Correspondence:
Kamal K Saha, CQ University, Bruce Highway, Rockhampton, Queensland 4702, Australia,
E-mail: k.saha@cqu.edu.au

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Introduction

The Australian tropical coastline extends for thousands of kilometers and most of Australia's population centers are along the coast. Any coastal community in the tropical region is exposed to the buffeting from extreme monsoonal events every year. Landfalling tropical cyclones are the major hazards that cause enormous sufferings to the communities in coastal fringes. According to Palmen [1] and Pielke [2] the Australian basin is one of the seven major basins among the world's tropical oceans which experience tropical cyclones - about 15%-20% of the world's total [3] but their pathways are substantially more erratic. Given the tremendous socioeconomic impact of landfalling tropical cyclones, the research focus on this particular topic is still very low in Australia. This is despite the opinions of many researchers such as Jagger *et al.,* [4], who stated that landfalling tropical cyclones' characteristics should be the prime focus in research.

However, elsewhere in the world, considerable work has been done on studying landfalling TCs. According to Marks and Shay [5] research on landfalling tropical cyclones has attracted keen interest in the U.S. Weather Research Program. TCs landfalling pattern and the impact of ENSO on it have been studied by Saunders *et al.,* [6] for hurricanes in the Atlantic and typhoons in the Western North Pacific basin. Applying landfalling Incidence Rate Ratio (IRR) method they found significant results for storms in Vietnam and typhoons in the Philippines. In another study based on bootstrap technique, Wu *et al.,* [7] reported that the number of landfalls decline in the late season of El Nino years for Western North Pacific basin except for Japan and Korean Peninsula, whereas part of this basin such as China is likely to have more landfalls in the late season of La Nina years.

Vescio *et al.,* [8] studied the potentiality of tropical cyclones to turn into tornadoes near the landfall point in the Atlantic and Gulf of Mexico. They opined the midlevel dry intrusions of landfalling TCs are responsible to alter the thermodynamic structure of TCs and transform them as the outbreaks of tornadoes. Later on, Curtis [9] examined this issue by a systematic experiment with a group of historical outbreak cases in the Atlantic and Gulf of Mexico and concurred with the results.

Ooyama [10] and Rosenthal [11] studied the impact of surface boundary conditions on landfalling TCs during and prior to landfall. Tuleya and Kurihara [12] studied the impact of land friction and evaporation on landfall through three simulated experiments. They found the evaporation depletion over land as the important parameter during landfall. Tuleya *et al.,* [13] used a detailed model for the study and found that the wind evolution, pressure and rainfall during TCs' landfall are sensitive on different surface conditions. Another research of Tuleya [14] established that the thermal property of land surface has significant impact on TC intensity and decay after

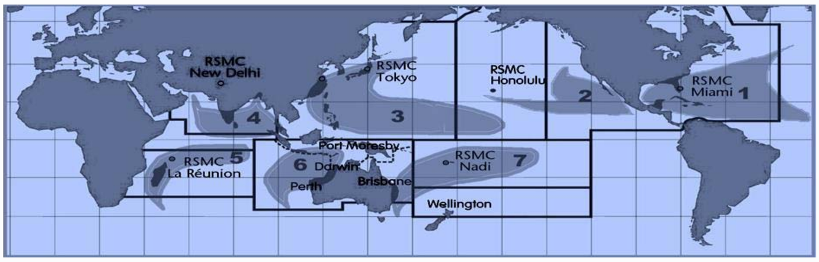

Figure 1: Map showing the seven global TC basins (numbered grey areas): (1) North Atlantic, (2) Eastern north Pacific, (3) Western north Pacific, (4) North Indian, (5) Southwest Indian, (6) Southwest Indian/Australia, and (7) Southwest Pacific/Australia. The official TC areas of responsibility, according to the World Meteorological Organization, are outlined in dark lines with the corresponding Regional Specialized Meteorological Centre (RSMC) for each area identified. Image courtesy of NOAA's Hurricane Research Division

landfall. Chan and Liang [15] analyzed the overall physical processes of landfalling TCs which tend to change during landfall. They ran four experiments in different land characteristics and concluded that the land moisture and land roughness have significant impact on changes of landfalling TCs structure at landfall.

In Australia, most of the research on tropical cyclones have been on tracking TCs. According to Elsberry [16] a tropical cyclone positioned off the east coast of Queensland with eastward component of motion usually goes away from the coast. Walsh [17] studied the probability of strike of a tropical cyclone at Queensland coast for a given position in the ocean and its translation. Dare and Davidson [18] studied the characteristics of tropical cyclones in the Australian region for the period 1963 to 2002, and they found the TC natures are quiet erratic here.

The Australian Bureau of Meteorology (BoM) usually offers 72 hours of forecasting lead time for tropical cyclones. Recent developments in meteorological knowledge and technology together with rising coastal vulnerability have increased public's expectations that demand further development in forecasting of tropical cyclones [19]. For a given offshore location and motion of a tropical cyclone, it should be possible to enhance forecasting lead time with modern knowledge [17]. However, Vigh [20] points out that in the past few decades official track errors have decreased each year by an average of 1.0% at 24h, 1.7% at 48h, and 1.9% at 72h but as we approach the atmosphere's inherent predictability limit, improvements would be difficult and, furthermore, numerical models have a practical limit of a few days of forecasting. Such forecasting lead times are often inadequate for disaster planning and management, and therefore, the focus of this research is on longer lead time forecasting. The primary objective of the present study has been to seek foreknowledge of an impending landfall beyond what a TC tracker can capture in a complementary framework of the probabilistic relationship between the Main Development Region (MDR) and the point of landfall in the Australian region.

The paper is organized such that in section 2 we describe the Australian basin in the context of the global basins. Section 3 provides some features of the data used in this study. In section 4 we develop a predictive model that can differentiate between a landfalling and a non-landfalling TC. Section 5 is on descriptive statistics of Australian landfalling cyclones. Section 6 attempts to discover the relationship between MDR and propensity to landfall. Section 7 presents a brief overview of models used in TC tracking and how the present study can fit in that mosaic. Some concluding remarks are made in section 8.

Global Perspective and the Australian TC Region

On the basis of TC genesis area Neumann [21] defined seven main TC basins in the world, they are as follows:

1. North Atlantic basin (North Atlantic Ocean, Caribbean Sea, Gulf of Mexico),

2. Eastern north Pacific basin (North America to 180° and north of the equator),

3. Western north Pacific basin (west of 180° including the South China Sea),

4. North Indian basin (Bay of Bengal and Arabian Sea),

5. Southwest Indian basin (South Indian Ocean west of 100°E),

6. Southeast Indian/ Australia basin (Southern Hemisphere 100°E-142°E) and

7. Southwest Pacific/ Australia basin (Southern Hemisphere east of 142°E).

Figure 1 gives a map of the world with the TC basins and related information. From the figure it is apparent that Australia straddles two basins - southeast Indian and southwest Pacific. The Australian Bureau of Meteorology has specified three tropical cyclone sub-regions for Australia, which are: western sub-basin bounded by latitudes 100^0S to 35.5^0S and longitudes 900^0E to 129.5^0E; northern

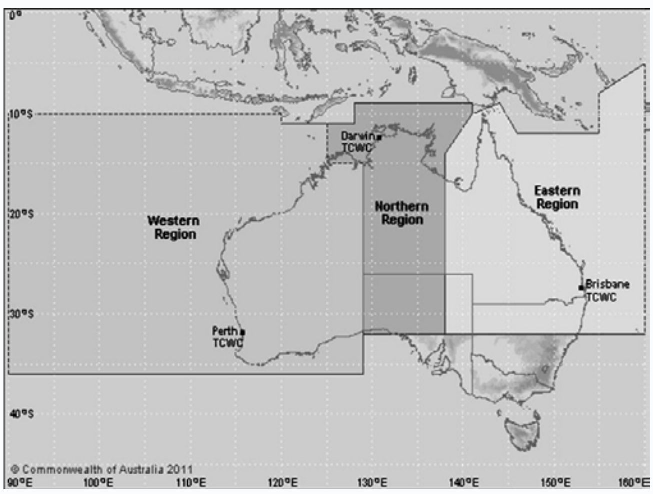

Figure 2: Australian continent with different tropical cyclone sub-basins. Source: Australian Bureau of Meteorology

Table 1: Cell references for the whole of Australian region. The left column gives longitude ranges in degrees and the top row gives latitude ranges in degrees.

Lon\Lat (deg)	0-5	5-10	10-15	15-20	20-25	25-30	30-35
90-95	0101	0201	0301	0401	0501	0601	0701
95-100	0102	0202	0302	0402	0502	0602	0702
100-105	0103	0203	0303	0403	0503	0603	0703
105-110	0104	0204	0304	0404	0504	0604	0704
110-115	0105	0205	0305	0405	0505	0605	0705
115-120	0106	0206	0306	0406	0506	0606	0706
120-125	0107	0207	0307	0407	0507	0607	0707
125-130	0108	0208	0308	0408	0508	0608	0708
130-135	0109	0209	0309	0409	0509	0609	0709
135-140	0110	0210	0310	0410	0510	0610	0710
140-145	0111	0211	0311	0411	0511	0611	0711
145-150	0112	0212	0312	0412	0512	0612	0712
150-155	0113	0213	0313	0413	0513	0613	0713
155-160	0114	0214	0314	0414	0514	0614	0714
160-165	0115	0215	0315	0415	0515	0615	0715
165-170	0116	0216	0316	0416	0516	0616	0716
170-175	0117	0217	0317	0417	0517	0617	0717

Table 2: Decade wise total occurrences of TCs in various genesis cells. Among those the number that made landfalls is identified in the second last column and the last column provides the relative frequency of landfall for only those cases where the total number of TCs exceeds 6.

Genesis cell	Decades							Total	No. of Landfall	Relative frequency
	1940s	1950s	1960s	1970s	1980s	1990s	2000s			
0101				2	1	1		4	1	
0102			2				1	3		
0103					1			1		
0114				1				1		
0201		2	1	9	4	2	2	20	2	0.10
0202		6	7	7	4	3	2	29		0.0
0203		1	1	7	8		1	18	1	0.06
0204				1		2		3		
0206	1				2	1		4	2	
0207		1		2	1		1	5	3	
0208		1	1	1	3	3		9	4	0.44
0209		3	4	4	1		1	13	8	0.62
0210				3			4	7	4	0.57
0211					1		1	2	1	
0212	1							1	1	
0213			1	3				4		
0214	1	4	1	2	2			10	2	0.20
0215			4	1		1		6	2	
0217				1				1	1	
0301		1	2	7	3	2		15		0.0
0302		3	3	2		6		14		0.0
0303			5	2	3	3	2	15		0.0
0304		4	3	1	4		1	13		0.0
0305		1	5	5	8	5	6	30	8	0.27
0306	1	2	4	7	3	6	5	28	15	0.54

0307	3	8	6	7	7	9	3	43	22	0.51
0308	2		6	6	3	8	3	28	18	0.64
0309	2	5	4	2	3	5		21	18	0.86
0310	1	4	10	11	8	6	8	48	46	0.96
0311	2	3	1	2	5	6	3	22	16	0.73
0312	2	3	2	1	4	3	1	16	7	0.44
0313	1	3	3	4	6	2	2	21	8	0.38
0314	4	3	4	6	4	5	1	27	9	0.33
0315		6	5	3				14	5	0.36
0316			1			1		2		
0317					1			1	1	
0401						1		1		
0402		1				1		2		
0403	1				1			2		
0404	1	2	2					5	1	
0405	2	3		1	1			7	3	0.43
0406	2	4	3	1	5	1	1	17	9	0.53
0407	1	2	5	8	1	3	2	22	13	0.59
0408					2		1	3	1	
0410	1	2		3	2	3		11	10	0.91
0411				1	1	1		3	3	
0412	1	1	3	8	4	4	3	24	10	0.42
0413	1	2	3	6	1	3		16	9	0.56
0414	1	5		2	2	2	3	15	2	0.13
0415	1	2	2	3	1	2		11	4	0.36
0416		1	2	1		1		5	4	
0417		1						1	1	
0503		1	1	1				3		
0508					1			1	1	
0512				1			1	2		
0513	1	4	1	1				7	3	0.43
0514			1					1		
0516		1						1		
0613			1		1			2	1	
Total	34	96	110	147	113	102	59	661	280	

sub-basin bounded by latitudes 90^{0}S to 32^{0}S and longitudes 129.5^{0}E to 137.5^{0}E; and eastern sub-basin bounded by latitudes 100^{0}S to 32^{0}S and longitudes 137.5^{0}E to 160^{0}E. Figure 2 provides the map of different Australian sub-basins along with the principal monitoring centers. Thus, the Australian TC region is quite extensive from 900^{0}E to 160^{0}E.

For the purpose of this study, to capture the spatial statistical characteristics, the whole Australian region is divided into grids. Each grid cell has a size of 5^{0} latitude by 5^{0} longitude. Each cell is referenced as given in Table 1. For any cell number, the first two digits refer to latitude and the last two digits refer to longitude. For a given cell, the calculation of cell boundaries is as follows:

Northern boundary = [First two digits×5-5] degrees south

Southern boundary = [First two digits×5] degrees south

Western boundary = [Last two digits×5-5+90] degrees east

Eastern boundary = [Last two digits×5+90] degrees east

Australian cyclone season starts on 1 November and lasts until 30 April of the following year. For the convenience of referencing, we will use in the sequel only the starting year to indicate the entire cyclone season.

Australian Tropical Cyclones (TCs) During the Period 1946-2006

According to the American Meteorological Society's glossary, the expression tropical cyclone is "the general term for a cyclone that originates over tropical oceans" [22]. However, for the purpose of this study, we restrict the analysis to the warm-core non-frontal synoptic scale low pressure systems organized with deep convection and surface wind circulation around a center with sustained gale force wind speeds of 34 knots (63 km/hr) or above. Such description fits in line with BoM's interpretation of TCs.

a. Data source

Jarrell [23] and Templeton and Keenan [24] argued that any study on landfalling TCs requires the use of the historical best track database of tropical cyclones and knowledge about the errors. Therefore, the data used in this study have been collected from the "best track" database of the Australian Bureau of Meteorology. To develop confidence in the outcomes of this study another data source, Joint Typhoon Warning Centre (JTWC), is also used for cross checking. In case of discrepancy, investigations were conducted to seek out the veritable values and thanks to BoM staff for their patience in such quest. Previously, JTWC data were not considered reliable, but after they have revised the data, it is widely accepted as a reliable source of data. Unfortunately, for data prior to 1946, we could not put sufficient faith on the reliability of the data to include in this analysis. Similar opinion has been expressed by Vigh [20] who stated that reliable statistics on Atlantic tropical cyclones only extend back to 1944 when aircraft reconnaissance began.

b. History and trends

Every year a number of tropical cyclones occur in the Australian basin. During the period 1946 to 2006 the total number of tropical cyclones formed in the Australian basin is 661. All the sub-basins contributed significantly to this number. In Table 2 a decade wise breakdown of all the tropical cyclones within this period is presented where the left column contains the genesis cells and the rightmost column the probability of landfall; of course, the probability values are only meaningful when the total number of occurrences are 6 or more. This number is arrived at with the sample size required to construct a 95% confidence interval that does not contain zero with normal approximation for a given proportion. (For computational details the reader is referred to page 295 of Levine *et al.,* [25]. Figure 3 provides similar information but for different sub-basins instead of genesis cells. The decade wise occurrence of tropical cyclones varied from 96 to 147 and, most of them did not make landfall. The highest occurrences were in the 1970s - the decade that spans 1971 to 1980. Remarkably, the percentage of landfall to the total generated is almost constant, roughly around 40 percent, which means the more the number of cyclones being generated the more will make landfalls. Figure 4 presents similar information as Figure 3 except that only the landfalling cyclones are counted. During the 61-year period the western sub-basin generated 315 TCs of which 93 made landfalls, the eastern sub-basin generated 214 TCs of which 90 made landfalls, and the northern sub-basin generated 132 TCs of which 97 made landfalls. The fact that the western sub-basin produced the maximum number of TCs could be the manifestation of the effect of Indian dipole. The overall annual mean number of occurrences is 11 with a Standard Deviation (SD) of 3.37. There does not appear to be any persistence or autocorrelation in the record, which means that one cyclone season does not affect the next one; the autocorrelation and partial autocorrelation functions are given in Figures 5 and 6. Although the enveloping curves for insignificant values in the two figures are crossed at lag one, both autocorrelation and partial autocorrelation values are 0.284, which means very little memory remains in one cyclone season of the previous cyclone season's occurrences. The periodograms of the sub-basins as well as of the total Australian basin showed no periodicity either at short term or at long term. This is rather uncommon because many climatic variables show decadal or multidecadal periodicities of some degree. The periodogram for the whole Australian basin is given in Figure 7, which reveals the flatness

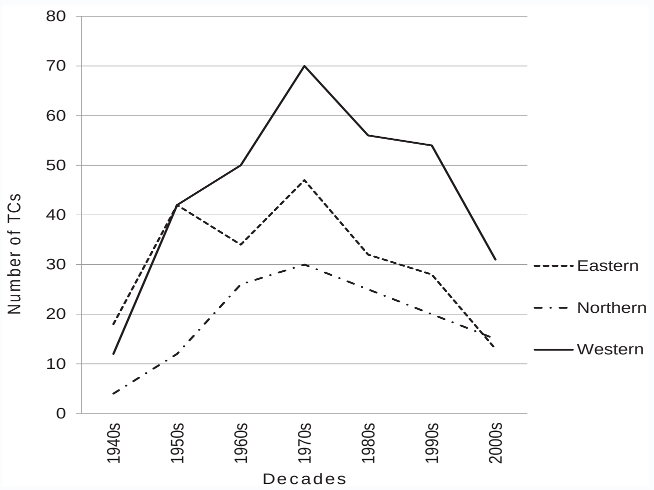

Figure 3: Graph showing the number of occurrences of tropical cyclones in different Australian sub-basins in various decades. The decade 1940s includes only the years 1946-1950 and the decade 2000s includes only the years 2001-2006.

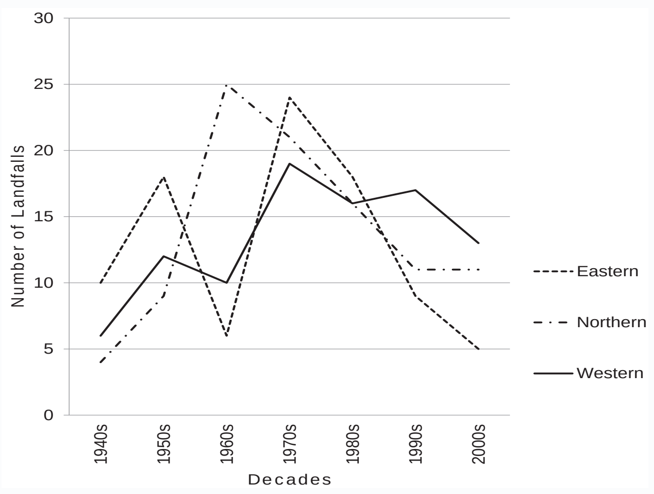

Figure 4: Graph showing the number of landfalling tropical cyclones in different Australian sub-basins in various decades.

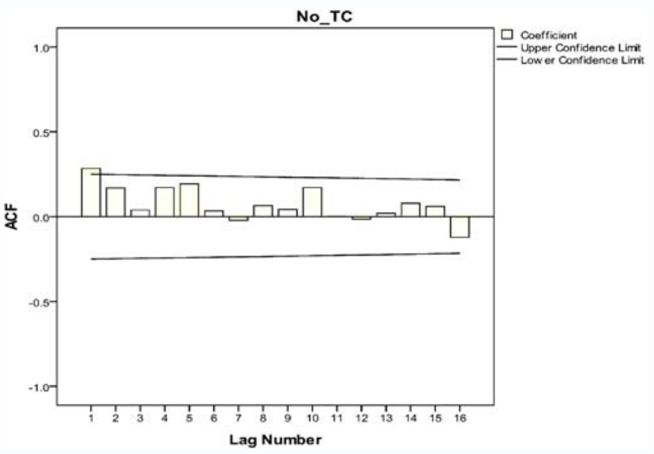

Figure 5: Autocorrelation function of the annual number of TCs in the Australian region.

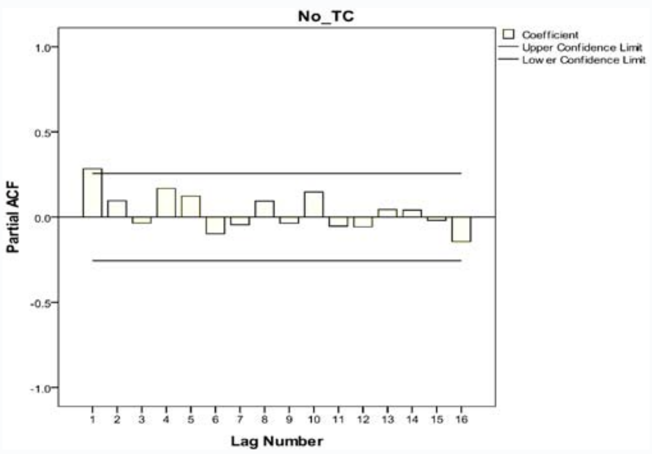

Figure 6: Partial autocorrelation function of the annual number of TCs in the Australian region.

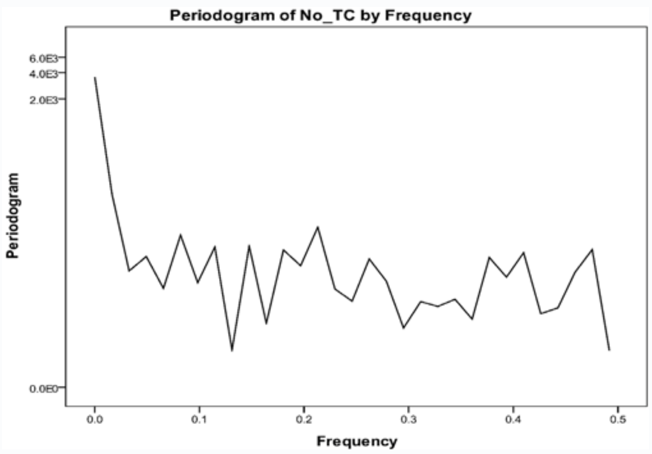

Figure 7: Periodogram of the annual number of TCs in the Australian basin.

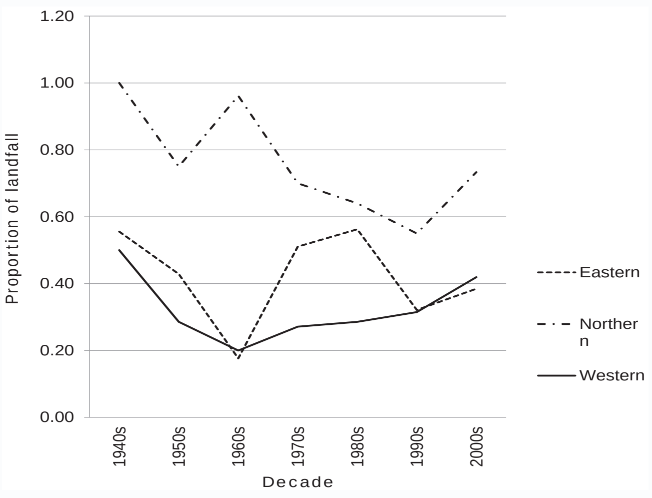

Figure 8: The proportion of TCs that made landfall in various decades and in different sub-basins of Australia during 1946-2006.

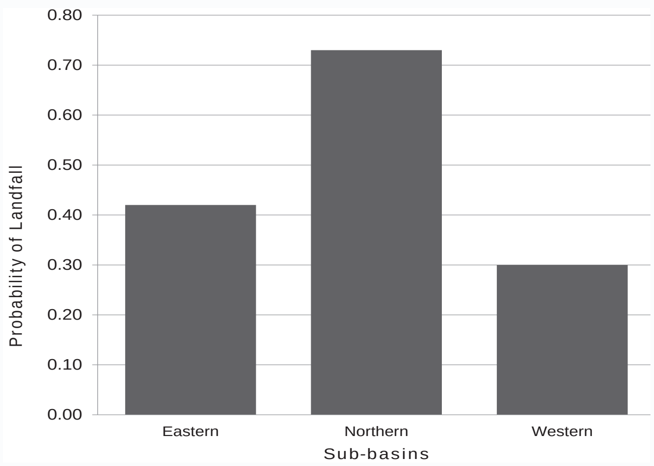

Figure 9: Probability of landfall in different sub-basins of Australia.

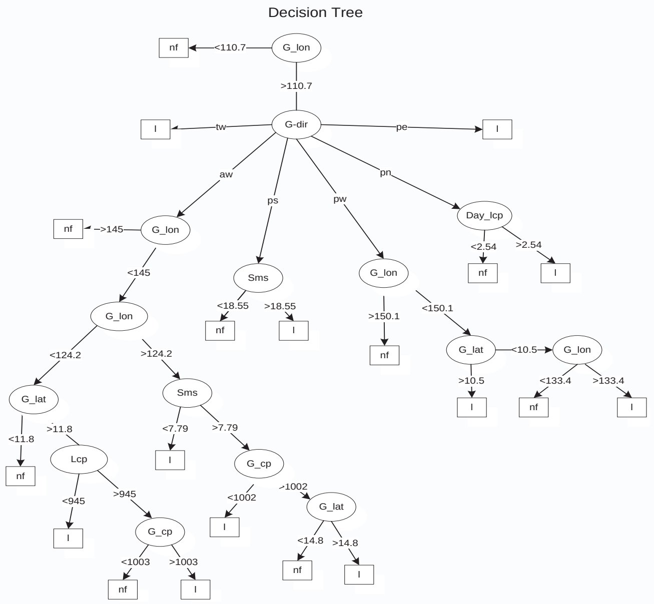

Figure 10: Decision tree generated by Weka for the Australian tropical cyclones. The terminal nodes are shown by rectangles - 'nf' is no landfall and 'l' is landfall.

in the curve.

The total number of landfalling tropical cyclones in Australia during the period 1946-2006 is 280. Figure 8 provides the proportion of landfall in different decades and also in different sub-basins and

Figure 9 gives the probability of landfall for the three sub-basins. The probability of landfall in the northern sub-basin is 0.73, which is quite high when compared with the eastern sub-basin that has a value of 0.42 and the western sub-basin that has a value of 0.30 - the overall probability for Australia is about 0.42. The relatively high value for the northern sub-basin is due to its land-locked geographical feature.

Distinguishing Features between Landfalling and Non-Landfalling Australian TCs

Usually, landfalling tropical cyclones are known as tropical cyclone as natural hazard when it makes landfall. But many occur in the sea every year, which is only known too well by the maritime users, the socioeconomic impact of non-landfalling TCs pale in comparison to the landfalling ones in Australia. Therefore, a useful research question is: Is there any distinguishing feature between a landfalling and a non-landfalling TC? To seek an answer, we adopt a data mining approach. After trying various applications of data mining strategies and techniques (such as artificial neural networks,

Table 3: Time and distance related statistics of landfalling TCs in different Australian sub-basins. The mean distances and their Standard Deviations (SDs) are given.

Description		Genesis to Termination		Genesis to LCP		LCP to Termination		Genesis to Landfall		Landfall to Termination	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Durati-on (days)	Eastern	8	5	4	3	4	4	5	4	3	1
	Northern	6	3	3	4	3	2	4	2	2	1
	Western	6	3	4	3	2	1	4	3	2	3
	Australia	7	4	4	3	3	2	4	3	2	2
Vector distance (D_d km)	Eastern	2099	1468	1127	1016	1189	935	1237	985	1030	1116
	Northern	1690	1337	866	874	983	819	671	672	1138	1252
	Western	1809	802	1090	806	1088	683	1246	714	921	806
	Australia	1846	1222	1019	897	1078	810	1034	829	1030	1071
Scalar distance (D_t km)	Eastern	3156	1849	1497	1025	1994	1495	1715	1222	1501	1423
	Northern	2449	1651	818	601	1672	1457	946	909	1487	1420
	Western	2960	1490	1265	704	1779	1436	1773	1168	1066	1129
	Australia	2846	1688	1182	834	1809	1461	1457	1160	1340	1333

support vector machines, association rule mining, etc.) with the software product WEKA we find the decision tree algorithm J48 to be useful for the purpose. J48 is the WEKA version of ID3 [26] that uses information theory principles with Shannon's entropy measure. The concept of the application of decision tree in the analysis of tropical cyclones however is not new, Hoyos *et al.,* [27] applied it to model the genesis of TCs. Another important reason to choose decision tree algorithm has been to be able to generate production rules.

From the BoM best track database all tropical cyclones during the period 1946-2006 were selected to test for the criterion of landfall. The independent variables chosen were based on literature survey as well as filtering mechanism used in data mining. The variables chosen are genesis latitude and longitude positions, genesis central pressure, displacement direction within 6 hours of genesis, lowest central pressure achieved, time taken to achieve this lowest central pressure, and the translation speed at genesis. The J48 pruned tree output is given in Figure 10.

The model provided an accuracy of 74% with 10-fold cross validation, which is one of the rigorous ways of validating a model and, the value is significant enough to demonstrate the usefulness of the decision tree. The production rules corresponding to the decision tree are provided in Display 1. The abbreviations used are: l = Landfall, nf = No Landfall, G_lon = Longitude Of Genesis Point, G_lat = Latitude Of Genesis Point, G_cp = Central Pressure At Genesis Point, G-dir = Initial Displacement Direction which are tw (towards land), aw (away from land), ps (parallel to land but south), pw (parallel to land but west), pn (parallel to land but north), and pe (parallel to land but east), Lcp = Lowest Central Pressure, Day_lcp = number of days required to reach at the start of lowest central pressure, and Sms = Storm Translation Speed. Some of the production rules have very high accuracy such as Rule 1 (90.42%), Rule 4 (86.36%), Rule 7 (84.62%), Rule 10 (86.96%), Rule 11 (76.57%), Rule 12 (82.29%) and Rule 13 (68.42%). These accuracies are for sample sizes of greater than 20, and therefore, have reasonable ground to be trusted. A few production rules yielded accuracies of 100%, but the number of occurrences is too low to rely upon. Therefore, it can be deduced that with the variables under consideration some production rules are very significant in distinguishing landfalling from the non-landfalling tropical cyclones.

Characteristics of Australian Landfalling TCs

a. Time related statistics

The critical stages of a landfalling TC are its genesis, maximum intensification, lowest central pressure, landfall and termination. These are the points of regime shift of a tropical cyclone's life cycle. Among these, the time and point of landfall is of most interest for disaster management. At this point, a TC undergoes major changes in its properties due mostly to starvation of moisture that feeds the system. Table 3 provides the time related statistics for all these stages of the life of landfalling TCs in Australia. The mean longevity overall is 7 days. The eastern sub-basin has relatively higher average lifetime and standard deviation suggesting greater unpredictability. Another reason could be the distant location of the IOD zone where most of the TCs in this sub-basin form. However, time to reach the lowest central pressure is similar suggesting that the length of time needed to reach the maximum intensity is roughly the same.

b. Distance related statistics

Distances travelled at different stages of a TC's life are analyzed in this section. It is evident from the Figure 11 that most of the tropical cyclones usually travel in zigzag ways. So, it is useful to consider both the vector and scalar distances in their tracks. Vector distance is the straight-line distance between two points often called "Displacement" and the scalar distance is the total distance covered by a TC along its track. Mathematically, they can be expressed as follows:

Displacement,

$$D_d = \sqrt{(LATD)_j^2 + (LOND)_j^2}$$

where $LATD_{ij}$ is the difference in kilometers along the latitude between i^{th} (starting) point and j^{th} (end) point and $LOND_{ij}$ is the difference in kilometers along the longitude between i^{th} (starting) point and j^{th} (end) point.

Distance Traversed,

$$D_t = \sum \sqrt{\Delta(LATD)_j^2 + \Delta(LOND)_j^2}$$

where Δ represents small increments.

Using the above relationships, the distances between various

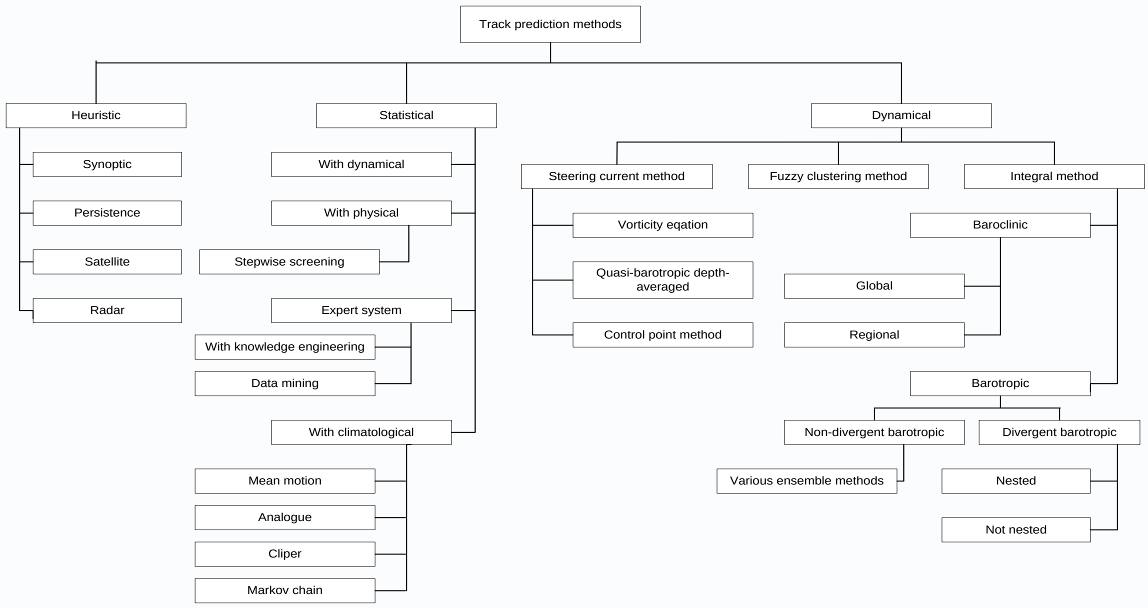

Figure 11: Various techniques used in tropical cyclone track prediction.

Table 4: Australian landfalling TCs movements along latitudes and longitudes. G_T is genesis to termination, G_MI is genesis to maximum intensity, MI_T is maximum intensity to termination, G_L is genesis to landfall, and L_T is landfall to termination.

Sub-basin	Movements	G_T	G_MI	MI_T	G_L	L_T
Eastern	Movement to higher Lat (%)	98.59	91.55	95.78	90.10	88.73
	Movement to lower Lat (%)	1.40	8.45	4.23	9.86	11.26
	Average change in Lat (deg.)	8.93	3.74	5.20	4.58	4.35
	Movement to higher Lon (%)	30.99	33.80	38.03	25.35	45.07
	Movement to lower Lon (%)	69.01	66.20	61.97	74.65	54.93
	Average change in Lon (deg.)	-6.84	-4.82	-2.01	-6.02	-0.82
Northern	Movement to higher Lat (%)	92.86	82.86	91.43	83.10	91.55
	Movement to lower Lat (%)	7.14	17.14	8.57	16.90	8.45
	Average change in Lat (deg.)	6.87	2.67	4.20	2.88	3.99
	Movement to higher Lon (%)	14.29	18.57	22.86	16.90	19.72
	Movement to lower Lon (%)	85.71	81.43	77.14	83.10	80.28
	Average change in Lon (deg.)	-3.45	-3.30	-0.14	-1.50	-1.90
Western	Movement to higher Lat (%)	100.00	98.59	95.77	100.00	97.18
	Movement to lower Lat (%)	0.00	1.41	4.23	0.00	2.81
	Average change in Lat (deg.)	11.92	5.38	6.54	6.87	5.05
	Movement to higher Lon (%)	38.03	5.63	76.06	12.68	73.24
	Movement to lower Lon (%)	61.97	94.37	23.94	87.32	26.76
	Average change in Lon (deg.)	0.49	-3.54	4.03	-2.72	3.20
Australia	Average change in Lat (deg.)	9.24	3.93	5.31	4.78	4.46
	Average change in Lon (deg.)	-3.27	-3.89	0.63	-3.41	0.16

stages of TCs for all the sub-basins were calculated and the results are given in Table 3.

Landfalling TCs have been found to have generally shorter tracks than the non-landfalling ones. The reason can be attributed to the sudden loss of speed and intensity as soon as a landfall is made. As can be seen in Table 3, the distance related statistics resonate well with the time related statistics. The landfalling TCs in the eastern sub-basin travel the longest distances and those in the northern sub-basin travel the shortest distances. The size and the land-locked nature of the northern sub-basin contribute towards the shorter sojourn of a TC.

How long a landfalling TC travels after genesis to achieve the maximum intensity varies for different TCs. The displacements before and after the point of maximum intensity are 1020 km (SD 900) and

Table 5: Average central pressures (hpa) in different stages of the life of a landfalling TC.

Australian sub-basins	Different stages of landfalling TC's life			
	Genesis	Max intensity	Landfall	Termination
Western	1001.93	947.28	955.50	998.13
Eastern	995.65	968.00	971.13	998.87
Northern	1000.96	968.17	970.00	996.38
Australia	999.52	961.15	965.54	997.79

1130 km (SD 1020), respectively for Australia. It is remarkable that both displacements have similar values and this fact is reflected in each sub-basin as well. Another interesting observation is that for the eastern and western sub-basins the maximum intensity is reached before a landfall is made but not so for the northern sub-basin. This could be due to the fact that a TC has to travel much shorter distance to make a landfall in the northern sub-basin.

c. Movement along latitude and longitude in various stages

Latitudinal and longitudinal movements at various stages of landfalling TCs appear to have distinct characteristics in Australia. These values are provided in Table 4. Most of the landfalling tropical cyclones move towards higher latitude but lower longitude to termination in all sub-basins, which fits with the general description of TCs moving poleward and westward, which according to Anthes [28] occur due to non-linear adjustment of poleward steering current. On average these movements are 8.93^0 in the Eastern, 6.87^0 in the Northern and 11.92^0 in the Western sub-basins along the latitude and 6.84^0 in the Eastern, 3.45^0 in the Northern and 0.49^0 in the Western sub-basins along the longitude. The average movement to the commencing point of maximum intensity is 3.93^0 along the latitude and 3.89^0 along the longitude for entire Australian basin.

In the event of landfall, the overall movements of TCs are 4.78^0 and 3.71^0 along latitudes and longitudes, respectively. But the journey from the point of landfall to its lyses does not maintain the usual course. Quite distinctly, these movements are from West to East. One of the reasons for this phenomenon could be the reverse force exerted by the increased friction of landmass. For Australia this positive longitudinal movement averages 0.16^0.

d. Lowest central pressure in various stages

Analyzing the data used in this study we found in most of the cases, genesis central pressures are the lowest for the Northern sub-basin. This may be the reason behind the most intense landfalling TCs occurring in the Northern sub-basin. At the commencement point of maximum intensity the average lowest central pressure (lcp) for Australia overall is 961.15 hpa and this value is lower by 38.37 hpa from the average of the genesis point. The lowest pressure however does not occur at the maximum intensity always, and according to Chan and Liang [15] the roughness of landmass could be a contributing factor to the phenomenon. Information about the central pressures at various stages of a TC's life is presented in Table 5.

Influence of MDR on Potential Landfall

The main development regions of tropical cyclones have been studied by numerous authors as to their cyclogenesis potential, but to the best of the authors' knowledge no one has addressed their influence on potential landfall. The motivation for research on this aspect lacked perhaps because TCs are believed to be translated by too many transitory factors in addition to the steering currents in which they are embedded. Nevertheless, statistically there can be meaningful patterns between a given MDR and landfall. The importance of environmental parameters of MDR to direct a tropical cyclone towards land is explored in this study for the Australian sub-basins.

The value of statistically relating an MDR with landfalling points lies in the fact that if the probability of cyclogenesis in a given MDR is known, we can relate that to landfall points and use that knowledge for long-term planning horizon relating to development planning and disaster management of a region. The results of our study relating MDR with points of landfall are captured in Table 6. In the table the numbering of grid cells follows the same nomenclature as defined earlier in Table 1. In the main body of Table 6 the conditional probability of genesis cell to landfall cell is given. For encapsulating significance, only the genesis cells which contributed to more than 6 to the number of landfalls are considered to calculate the conditional probability values. For example, the probability corresponding to the genesis cell 0314 that makes landfall in cell 0412 is 0.185, which means a TC generated in cell 0314 has 18.5% chance of striking land at cell 0412.

Most probability values in Table 6 are not high but they provide a clear indication of where the TC is likely or unlikely to hit. The whole table portrays a picture of landfalling tendency of TCs generated in the MDR cells. For instance, the table reveals that the TCs generated in the eastern and western sub-basins are more likely to make landfall in the same sub-basin whereas the northern sub-basin's TCs tend to make landfall both in the northern and western sub-basins. The highest probability values belong to the northern sub-basin which confirms more potentiality of this sub-basin.

Dynamic Forecasting

The overwhelming focus of research on TCs has been on forecasting their tracks. Despite this, a TC's track prediction has remained a challenging issue. However, myriads of research efforts have witnessed a prolific growth of TC track prediction techniques. Still, no one of the techniques has been proven to be outstanding in performance and superior from the rest. Figure 11 summarizes various techniques used so far - many of them are described in Mohanty and Gupta [29]. Most of the statistical techniques cited use predictors from one of the four sources which are climatology, persistence, environmental conditions and dynamics. Performance of these sources to reduce the error of prediction of TC tracks varies from basin to basin but is critical for the Australian basin [30-33].

The decision tree and production rules we presented in section 4 is a static formula. If this can be combined with any of the procedures identified in Figure 11, it would be possible to enhance the reliability of the forecast. The integration of the two can be done by recursive Bayesian integration or Kalman filter. The prior and posterior probability values can be assessed from the accuracies expected from the two procedures. To illustrate, suppose for a given position and history of a TC, one of the tracking methods predict hitting a given location *i* of land with a probability of p_t^i. And a production rule from the decision tree predicts hitting the same spot with a probability of p^i. Using Kalman filter [34] the updated probability, p_{s+1}^i, of hitting land at the given spot is given by:

$$p_{s+1}^i = A_s p_s^i + B_t p_t^i$$

Table 6: Probability of making landfall in a particular cell given the TC forms in a specified genesis cell. The table also provides additional information on the total number of TCs generated, the numbers that made landfall, and the overall probability of landfall for the given genesis cell.

Sub-basin			Eastern					Northern						Western					Total
Genesis cells →			312	313	314	412	413	209	308	309	310	311	410	305	306	307	406	407	
Landfall cell	Eastern	411	0.06							0.05	0.08	0.05	0.18						12
		412	0.06	0.05	0.19	0.29	0.25					0.05							22
		512			0.04		0.06												8
		513			0.07	0.08	0.06												11
		613	0.13			0.04	0.19												13
		717		0.05															1
	Northern	308						0.08	0.18	0.19	0.06				0.04				14
		309						0.23		0.33	0.10								16
		310								0.10	0.17	0.09	0.09						18
		311	0.19	0.29	0.04			0.08			0.29	0.27	0.18						35
		410						0.08		0.05	0.17	0.18	0.45						19
	Western	307									0.02					0.02	0.06		3
		406							0.04		0.04			0.03	0.04	0.07	0.06		9
		407						0.08	0.11		0.02	0.05		0.07	0.07	0.23	0.12	0.18	35
		408							0.04										1
		505							0.04	0.10					0.21	0.07	0.06	0.05	15
		506						0.08	0.21	0.05				0.17	0.11	0.09	0.18	0.18	34
		507																0.05	1
		605							0.04						0.07	0.02		0.09	6
		606																0.05	1
		706															0.06		3
Total no. of landfalls			7	8	9	10	9	8	18	18	46	16	10	8	15	22	9	13	226
Total no. of occurrences			16	21	27	24	16	13	28	21	48	22	11	30	28	43	17	22	387
Probability of landfall for			0.44	0.38	0.33	0.42	0.56	0.62	0.64	0.86	0.96	0.73	0.91	0.27	0.54	0.51	0.53	0.59	

where, state-transition coefficient,

$$A_s = \frac{p^i + \sum p^i_{s-1}}{p^i + \sum p^i_s}$$

and control input coefficient, $B_t = 1 - A_s$, and t is the number of the sequence at which updating is being done. To start the process of updating, $p^i_{s=1} = p^i_{t=1}$ and $p^i_{s=0} = 0$. To demonstrate how the weights of updating would change with sequence, we start with a hypothetical probability of 0.3 from the production rule and 0.3 from a tracking model. As the TC translates, we assume that the tracking probability improves by 5% each time. Figure 12 captures the progression of the state-transition coefficient (A_s) with sequence in such a situation, the figure also shows that even if the tracking probability initially is very different such as 0.4 or 0.5, A_s values tend to converge after a few sequences. There appears to be always some contribution from the production rule even after the TC has been monitored for quite some time.

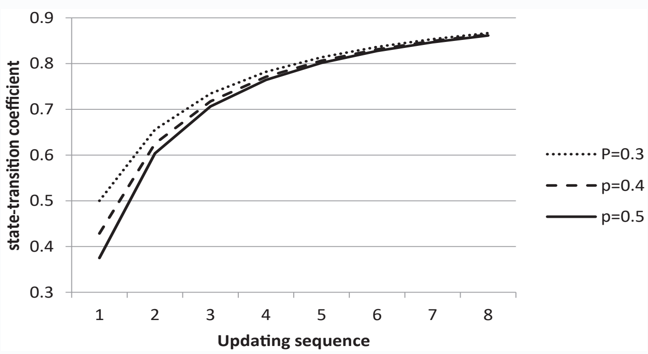

Figure 12: Change of state-transition coefficient with each sequence of updating for a static landfall probability value of 0.3. Three probability values of the tracking model are considered at initial values of 0.3, 0.4, and 0.5 (= *p*) and is assumed to increase by 5% with each sequence.

Conclusions

Statistical climatology for 61 years (1946-2006) of landfalling tropical cyclones in the Australian region is investigated in this study. The entire life of a landfalling TC is divided into three sections for easy interpretation. The elapsed time, distance and movement along the track of landfalling tropical cyclones at those sections are illustrated. Also, the probabilistic relationship between the Main Development Region (MDR) and the landfalling spots are examined, which could be an important regional planning tool to account for and hedge against the landfalling tropical cyclones.

The reason we specifically focused on landfalling tropical cyclones is the human sufferings they cause. We looked at the distinguishing features between landfalling and non-landfalling TCs. We came up with a decision tree model that yielded certain production rules which are statistically significant. We discovered that the Australian basin is unique in many ways, for example, there is no periodicity or cyclic pattern in the number and intensity of TCs generated each year but remarkably the proportion of those that make landfall is fairly constant interannually.

About 42% of all tropical cyclones generated in the Australian region make landfall each year, which amassed to 280 landfalls during the study period (1946-2006). On average, a landfalling tropical cyclone takes 4 days, with a standard deviation of 3, to reach the maximum intensity stage from genesis that may last for 1.23 days.

Two kinds of distance metrics between different stages of landfalling tropical cyclones are described in this study. They are scalar and vector distances. These two distances for a landfalling tropical cyclone in Australia are 1845.95 km (SD 660.09) and 2846.04 km (SD 1688.29), respectively for the entire life and are distinct from non-landfalling TCs - usually shorter but different for different sub-basins.

Analysis of the directions of movements of landfalling tropical cyclones' tracks confirm that the major latitudinal movements are towards higher values and longitudinal movements towards lower values. So, we can conclude that the general movement of landfalling tropical cyclones is towards the southwest. The average values of movements are 9.240 along latitude and 3.270 along longitude from genesis to termination in Australia. These findings are useful for planning.

However, what is perhaps the most important finding of this investigation for long-term regional planning and development is the conditional probability of landfall given that a TC is generated in a specified cell. If the probability distribution of cyclogenesis in the MDR is known, then the marginal probability of TC landfall in a given location can be calculated.

The benefit of this study lies in TC prediction rather than forecasting and, for the latter, there are many operational tools. However, it is possible to integrate the two to enhance the reliability of forecasts. We have provided an overview of the operational tools in common use.

Display 1. Production rules generated from the decision tree of Figure 10.

Rule 1: IF G_lon <=110.7 THEN No Landfall

Rule 2: IF G_lon >110.7 AND G-dir =tw THEN Landfall

Rule 3: IF G_lon >110.7 AND G-dir =pe THEN Landfall

Rule 4: IF G_lon >145 AND G-dir =aw THEN No landfall

Rule 5: IF 110.7 <G_lon<=124.2 AND G-dir =aw AND G-lat <=11.8 THEN No landfall

Rule 6: IF 110.7 <G_lon<=124.2 AND G-dir =aw AND G-lat >11.8 AND Lcp<=945 THEN landfall

Rule 7: IF 110.7 <G_lon<=124.2 AND G-dir =aw AND G-lat >11.8 AND Lcp>945 AND G_cp<=1003 THEN No landfall

Rule 8: IF 110.7 <G_lon<=124.2 AND G-dir =aw AND G-lat >11.8 AND Lcp>945 AND G_cp>1003 THEN Landfall

Rule 9: IF 124.2 <G_lon<=145 AND G-dir =aw AND Sms<=7.79 THEN Landfall

Rule 10: IF 124.2 <G_lon<=145 AND G-dir =aw AND Sms>7.79 AND G_cp<=1002 THEN Landfall

Rule 11: IF 124.2 <G_lon<=145 AND G-dir =aw AND Sms>7.79 AND G_cp>1002 AND G_lat<=14.8 THEN No Landfall

Rule 12: IF 124.2 <G_lon<=145 AND G-dir =aw AND Sms>7.79 AND G_cp>1002 AND G_lat>14.8 THEN Landfall

Rule 13: IF G_lon >110.7 AND G-dir =pn AND Day_lcp<=2.54 THEN No Landfall

Rule 14: IF G_lon >110.7 AND G-dir =pn AND Day_lcp>2.54 THEN Landfall

Rule 15: IF G_lon >150.1 AND G-dir =pw THEN No Landfall

Rule 16: IF 110.7<G_lon<=150.1 AND G-dir =pw AND G_lat>10.5 THEN Landfall

Rule 17: IF 110.7<G_lon<=133.4 AND G-dir =pw AND G_lat<=10.5 THEN No Landfall

Rule 18: IF 133.4<G_lon<=150.1 AND G-dir =pw AND G_lat<=10.5 THEN Landfall

Rule 19: IF G_lon >110.7 AND G-dir =ps AND Sms<=18.55 THEN No Landfall

Rule 20: IF G_lon >110.7 AND G-dir =ps AND Sms>18.55 THEN Landfall

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