Statistical modelling of tropical cyclones' longevity after landfall in Australia

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Most of the devastation caused by a tropical cyclone occurs on land, and therefore, its longevity after landfall is of critical importance. Published literature identifies many factors including inland environmental characteristics that influence this longevity as well as power dissipation rate. These have been studied in this research in the context of tropical cyclones that hit Australian coasts during the period 1984-2010. For obvious reasons, tropical cyclones which manifested recurrence or multiple landfalls have been excluded. After applying several statistical tools to the observed data, it has been found, from the list of variables identified in literature related to tropical cyclones, that storm intensity at landfall, translation speed, relative humidity, surface temperature, upper level divergence, and surface roughness exhibited statistical significance. However, stepwise regression retained only surface roughness and central pressure which yielded a coefficient of determination of 76 percent during calibration and 59 percent during validation with 60%/40% split in data. The influence of surface roughness is well understood, but as yet, no consistent metric for the purpose of tropical cyclones' propagation exists, and therefore, this paper introduces a method of assigning surface roughness based on terrain characteristics.

Introduction

Generally, when a tropical cyclone (TC) hits land with considerable fury, the damages are catastrophic. The longer a TC hovers on land, the greater usually are the damages to property and suffering to communities. It is this devastation of landfalling TCs that attracts widespread attention of the media and public. From an analytical perspective, it has been observed that landfalling TCs usually undergo a remarkable change in their properties as soon as they hit land (Bender et al. 1987) characterized by exponential decay. The underlying primary reasons are, first, the energy of the ocean (latent heat of condensation of water) is cut off, which causes a weakening of the pressure gradients and primary vortex, and second, the frictional dissipation of the wind field aided by increased resistance from topography. Thus TCs weaken after landfall albeit a very few that can re-intensify after landfall (for example, George, 27 February–12 March 2007 and Sam, 4-10 December 2000 which re-intensified after making landfall in Australia).

In most cases, a significant decrease in the intensity of TCs occurs within the first 12 hours after landfall (Ying et al. 2006; Brand and Blelloch 1974; Hubert 1980). This aspect has been captured in empirical models for the wind speeds of landfalling TCs with the basic assumption that the decay rate is proportional to the wind speed (Kaplan and DeMaria 1995). Kaplan and DeMaria's models were developed for the United States but other such models have been developed for other parts of the world, for example, Roy Bhowmik et al. (2005) developed a model for the Bay of Bengal coasts. There are many numerical models for TCs that are witnessing continuing improvements, where the decay characteristics after landfall are explained as a combined effect of atmospheric circumstances and TCs' own properties (e.g., GFDL hurricane model, NOAA) as well as influences of topography, specifically mountain ranges (Bender et al. 1987). Ramsay and Leslie (2008) applied the Pennsylvania State University – National Center for Atmospheric Research mesoscale numerical model (MM5) to TC Larry in Australia to assess the influence of coastal orography. However, the level of sophistication required

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in numerical models for a TC's intensity and track predictions after landfall with acceptable reliability is still beyond human reach (Roy Bhowmik et al. 2005), and the need for useful empirical models exists. According to Done et al. (2015) TCs continue to remain a hard test case for numerical modelling.

It is now widely accepted that surface roughness and reduced relative wetness in the atmosphere are the key factors for enhancing decay after landfall; and also, the thermal property on land may have a crucial role in the decay (Tuleya 1994). Furthermore, mountainous topography of a region may cause deflection and discontinuity (Lin et al. 2002) which contributes to decay. Lin et al. further developed from the explanatory variables three non-dimensional parameters, V_{max}/Nh, V_{max}/U and V_{max}/R_rf, and identified those as controlling parameters for the phenomena; where V_{max} is the maximum tangential wind speed of the TC, N is the Brunt-Väisälä frequency, h is the maximum mountain height, U is the basic flow speed toward the mountains, R_r is the radius of the maximum tangential wind, and f is the Coriolis parameter.

Zehnder (1993) and Farfan and Zehnder (2001) report the influence of the mountains of Mexico on TCs and note: that the orientation of landmass is important, that there is weakening of the storm intensity, acceleration of the translation motion, and a track deflection which occurs far upstream of the landfall area, and that there are formations of secondary circulations downstream of mountains even before a TC hits land. Tang and Chan (2015) noted that TCs approaching Taiwan are affected by anti-cyclonic gyre induced by the large landmass of China. Translation speed, maximum intensity and height of a mountainous range were found by Yeh and Elsberry (1993) to be the controlling parameters to shape the track and deflection of a TC when it interacts with the orographic region of Taiwan. No doubt, the decay characteristics of TCs after landfall are different for different regions, but it has been consistently observed that the stronger the TC, the faster the decay rate after the landfall event (Ying et al. 2006), and also, that the topographic and environmental parameters control the decay and duration of a TC after landfall.

In this paper an attempt is made to make a generalized inference about the topographic influence on TC climatology that takes into account the ground surface roughness owing to the type of ground cover and the degree of undulation of the land. The underlying reasoning is simple, such as, a barren land is likely to offer less resistance than a forest canopy, or a flat plain is likely to offer less resistance than an undulating terrain (without delving into the secondary vortices and wakes that the latter may generate). Land type is likely to have an effect as well, and fortunately in this study, we were able to observe the passage of TCs over deserts, scrubland, grassland, cultivated areas, forest canopy, lakes and swamps, and built-up areas. The process of inference is underpinned by statistical significance tests of the factors identified or alluded to in various literatures pertaining to the decay and duration of a TC after landfall.

Data for this study

The context for this study is the Australian basin which extends from 90^0E to 160^0E and 10^0S to 36^0S. Tropical cyclones which made landfall during the period of 1984 to 2010 are used in this study from the "Best Track" database of the Australian Bureau of Meteorology (BoM). The data can be accessed from the BoM website http://www.bom.gov.au/cyclone/history/index.shtml in the file named "Database of past tropical cyclone tracks." The data was extensively reviewed in 2007 and also updated in 2013. Some data were taken from other sources such as ECMWF and KNMI, which will be mentioned later. The cyclone season in this part of the world extends from November to May. For consistency, landfalling TCs with recurrence and multiple landfall events are excluded from the selection. A recurrent tropical cyclone is one that gathers strength after landfall (which can occur for various reasons such as wetland, and the reasons have not been investigated in this study) and, a multiple landfalling TC is one that moves back to the sea, to return to land again later. Also, the landfalling TCs with extra tropical characteristics are not considered because they may derive the majority of their energy from baroclinic processes. Table 1 provides the complete list of tropical cyclones considered in this study. In the table, the attributes of Year, Latitude, Longitude and Intensity (knots) relate to landfalling time and location. Also, the TC names provided in italics are those which have been used for model validation and the remaining TCs were used for model calibration.

Table 1 Database of Australian landfalling tropical cyclones used in this study.

Name	*Year*	*Lati-tude*	*Longi-tude*	*Inten-sity*	*Name*	*Year*	*Lati-tude*	*Longi-tude*	*Intensi-ty*
FERDINAND	1984	12.2	134.5	46	RONA	1999	16.1	144.6	46
EMMA	1984	21.2	116.8	37	ELAINE	1999	28.2	114.2	35
REBECCA	1985	12.9	141.7	40	GWENDA	1999	20.2	118.9	54
LINDSAY	1985	18.4	122.2	81	JOHN	1999	20.8	117.6	94
BILLY-LILA	1986	29.7	116.2	30	*ROSITA*	2000	18.5	122.5	103
ELSIE	1987	20.3	121	102	*WINSOME*	2001	14.1	135.9	59
ILONA	1988	21.6	116.2	78	*BERNIE*	2001	16.5	138.8	42
AIVU	1989	20	146.3	51	*CHRIS*	2002	20.1	120	121
ORSON	1989	21	116.3	118	*DEBBIE*	2003	11.8	133.6	66
IAN	1992	21.2	115.7	78	*FAY*	2004	20.2	120.1	103
NAOMI	1993	18.9	121.6	84	*CLARE*	2006	20.9	116.3	75
BOBBY	1995	21.7	115.2	98	*EMMA*	2006	21.3	115.9	46
WARREN	1995	16.8	138.8	84	*LARRY*	2006	17.5	146	94
KIRSTY	1996	20.1	119.5	108	*HUBERT*	2006	21.3	115.7	46
BARRY	1996	16.6	141.4	84	*JACOB*	2007	20.1	118.9	49
OLIVIA	1996	21.4	116	113	*DOMINIC*	2009	22.5	115.5	51
MAY	1998	17	139.1	46	*ULUI*	2010	20.1	148.2	72
THELMA	1998	14.7	125.2	84	*MAGDA*	2010	16.7	124.5	52
VANCE	1999	22.7	114.4	113					

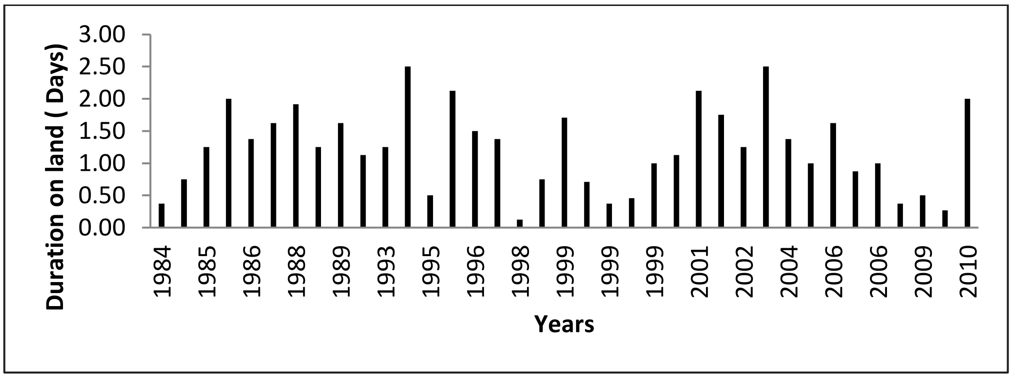
Duration on land of TCs

In Australia, the duration of a TC on land displays considerable variation from year to year and region to region. The inter- and intra-annual and inter-regional variations of the duration of landfalling TCs for the period 1984-2010 are presented in Figure 1. (Duration here has the same meaning as the best track database of BoM, and is measured in days until the TC's wind speed at 1-min interval goes below 46 km/hr or 25 knots.) We can notice from the figure that durations were high in 1994, 2003 and 2010, but there is no identifiable significant pattern (contrary to the argument that global warming may increase TC duration (Emanuel 2005)). There is some variation in durations between months as can be seen in Figure 1(b), but these have been found to be statistically insignificant. The environmental factors which could reduce the duration are lower sea surface temperature and lower higher level divergence (source: personal communication with Australian Bureau of Meteorology experts).

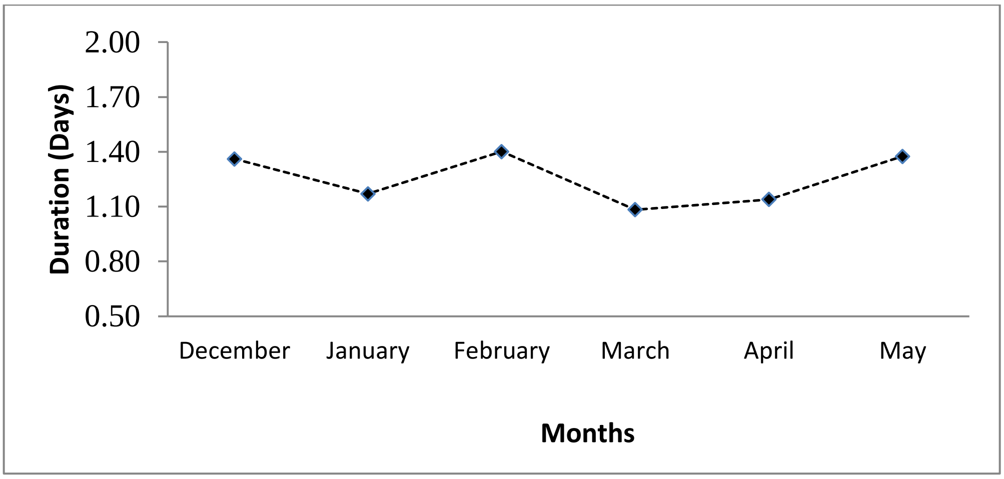
The impact of sub-region is not significant either though noticeable in Figure 1(c). The Australian Bureau of Meteorology has specified three TC sub-regions for Australia, which are: Western sub-basin bounded by latitudes 10°S to 35.5°S and longitudes 90°E to 129.5°E; Northern sub-basin bounded by latitudes 9°S to 32°S and longitudes 129.5°E to 137.5°E; and Eastern sub-basin bounded by latitudes 10°S to 32°S and longitudes 137.5°E to 160°E. The Western sub-region appears to have the longest duration. The Northern sub-region shows the second longest duration. These could be due to the jet stream that flows west to east through the heart of Australia.

To assess the statistical significance of the differences, a pairwise student *t*-test was conducted and all estimated values were below 0.5, far below the critical values, suggesting that adequate distinct patterns do not exist in the data to infer month-wise or region-wise variations.

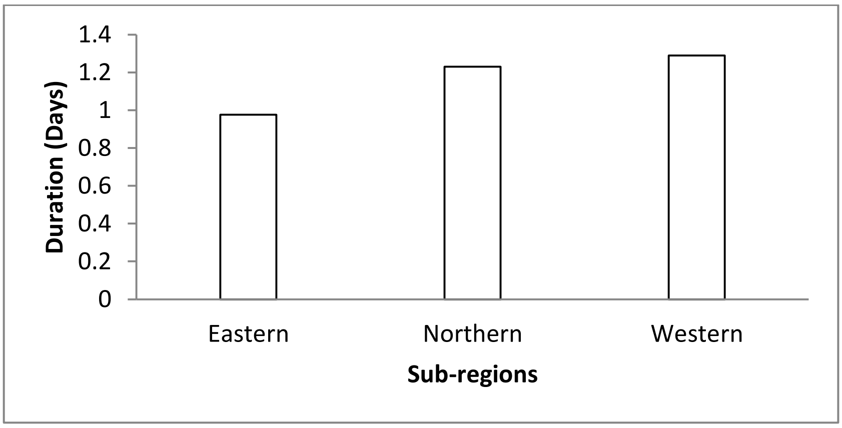
Figure 1 Tropical cyclone durations after landfall during the period 1984-2010 in the Australian basin.



(a) Sequence of duration of individual TCs



(b) Monthwise duration



(c) Sub-regionwise duration

Factors that influence TC duration on land

Quite a few scientific studies have been conducted in the past to determine the influencing factors of TC movement while encountering landmass, especially mountain ranges (Brand and Blelloch 1974; Wei and Chang 1982; Lin et al. 2002). Usually, a tropical cyclone tends to commence decaying just after making landfall. Malkin (1959) reported that more intense hurricanes tend to fade more rapidly and the maximum wind speed at any time after landfall is a function of wind speed and translation speed at the point of landfall (this is also supported by Kaplan and DeMaria 1995). Put simply, the disconnection from the warm ocean strips the TC from its source of fuel, which is the latent heat, and the remaining life is akin to the momentum that is driving it, attenuated by resistive forces. Chen (1998) reported that the longevity of a TC after landfall is closely related to the moisture supply, energy from baroclinic sources, and upper air divergence. Lianshou and Zjiyong (2002) observed that most of the longer sustained landfalling TCs are associated with the strong divergence in the upper level atmosphere. Montgomery et al. (2001) attempted to model the spindown dynamics of hurricane-like vortices using Navier-Stokes equations and found that the half-life of a TC is a function of fluid depth, but their assumptions of axisymmetric flow, homogeneous incompressible fluid and uniform boundary conditions need further scrutiny.

Kaplan and DeMaria (2001) studied the decaying landfalling TCs in the United States and revealed that those which made landfall to the north of 37^0N latitude decayed more rapidly than those making landfall south of 37^0N. The reason identified was higher terrain near the coast. A study for the east coast of the United States revealed that dissipation of a landfalling TC is faster along the Atlantic coast than either the Mexico or Florida coastline (Hubert 1955) – an observation that is as yet difficult to explain.

Kaplan and DeMaria (1995) introduced the concept of a reduction factor R' to account for the effect of land surface roughness on the intensity of landfalling tropical cyclones and found an optimal value of R' to be 0.9. In this present study, scatter plots have been drawn for all the factors which have been identified as potential explanatory variables for the decay against duration to get a first visual impression of the influence. From our data, none of the scatter plots showed any significant pattern except two – duration versus central pressure and duration versus land surface roughness. We have also studied the correlation matrix of all the variables identified in literature, which is presented in Table 2 from SPSS (Statistical Product and Service Solutions) output. In the table, the TC's duration (*Dur*) is in hours, latitude and longitude (*Lon*) are in decimal degrees, central pressure (*Cp*) is in hectopascals (hPa), relative humidity (*Rh*) is at 2m/10m elevation, storm translation speed (*Sms*) is in km/h, temperature (*Temp*) is in ^{0}C at 2m/10m elevation, divergence (*Div*) is at 700mb in unit of per hour, and land surface roughness (*R*) comes from the relationship given later in the paragraph after equation (4). The values of *Rh*, *Temp* and *Div* were taken from the KNMI (Royal Netherlands Meteorological Institute) website http://climexp.knmi.nl/.

Looking at the correlation matrix, it is apparent that the significant variables are *Cp*, *Div* and *R*. To further test for the significance we did a principal component analysis. The result of the principal component analysis is presented in Table 3. SPSS identified only two principal components. But the decay in the eigenvalues is neither sharp nor abrupt anywhere down the column. EOF1 (moist and slow moving) appears to be related to boundary layer stability and EOF2 (high *Cp*, low temperature, divergence) seems to be related to TC intensity. To check for robustness of the analysis we further performed factor rotation, specifically, varimax rotation, which did not yield any different outcome than the two significant eigenvalues. This approach identified significant contributions of the variables toward characterization of a TC but did not further our cause to identify the explanatory factors for duration.

Thus a different approach was adopted to identify the significant independent variables through stepwise regression. Stepwise regression can be routinely done through SPSS – it uses Efroymson's (1960) method of forward selection. With the default parameters provided in SPSS for the stepwise regression, our calibration data yielded the following formula:

$$TC\ Duration = 402.24 - 0.375Cp - 43.57Div - 233.04R \quad (1)$$

Equation (1) provided a Coefficient of Determination (R^2) value of 0.70. However, if we remove divergence, the regression equation we get is:

$$TC\ Duration = 391.62 - 0.37Cp - 241.71R \quad (2)$$

which yields a R^2 value of 0.68. But with adjusted R values, as discussed later, the R^2 value for the latter equation becomes 0.76 and the equation changes to

$$TC\ Duration = 399.16 - 0.37Cp - 283.07R \quad (3)$$

The issue of upper level divergence deserves some discussion. Strong divergences usually arise from a subtropical anticyclone or aloft jet stream. Transition into landfall in their presence would provide a TC with baroclinic energy from the mid-latitude cold air. TCs over land then become a hybrid structure with half warm and half cold. The potential energy of the solenoid hybrid system converts into kinetic energy resurrecting the vortex circulation. We collected divergence data from ECMWF (http://appps.ecmwf.int/datasets/data/interim-full-daily/) and found that divergence data varied rather wildly from storm to storm during the passage of a TC over land. Percentage changes varied from near zero percent to several hundred percent from the point of landfall to the lysis point of a TC, both in the positive and negative values though large shifts were mostly in the positive values.

Table 2 Correlation matrix of all cited explanatory variables for Australian landfalling TCs' durations.

Pearson correlation		*Dur*	*Lat*	*Lon*	*Rh*	*Cp*	*Sms*	*Temp*	*Div*	*R*
Dur	*Correlation Coeffi.*	1.000	.364	-.306	-.133	-.600**	.056	.406	.687**	-.899**
	Sig. (2-tailed)		.096	.166	.554	.003	.803	.061	.000	.000
Lat	*Correlation Coeffi.*	.364	1.000	-.880**	-.704**	-.094	.555**	.170	.258	-.294
	Sig. (2-tailed)	.096		.000	.000	.678	.007	.449	.247	.184
Lon	*Correlation Coeffi.*	-.306	-.880**	1.000	.556**	.223	-.436*	-.211	-.202	.195
	Sig. (2-tailed)	.166	.000		.007	.319	.042	.347	.368	.385
Rh	*Correlation Coeffi.*	-.133	-.704**	.556**	1.000	-.035	-.815**	-.096	-.327	.092
	Sig. (2-tailed)	.554	.000	.007		.876	.000	.671	.137	.685
Cp	*Correlation Coeffi.*	-.600**	-.094	.223	-.035	1.000	.149	-.449*	-.691**	.440*
	Sig. (2-tailed)	.003	.678	.319	.876		.509	.036	.000	.040
Sms	*Correlation Coeffi.*	.056	.555**	-.436*	-.815**	.149	1.000	-.096	.194	-.009
	Sig. (2-tailed)	.803	.007	.042	.000	.509		.671	.388	.968
Temp	*Correlation Coeffi.*	.406	.170	-.211	-.096	-.449*	-.096	1.000	.511*	-.359
	Sig. (2-tailed)	.061	.449	.347	.671	.036	.671		.015	.101
Div	*Correlation Coeffi.*	.687**	.258	-.202	-.327	-.691**	.194	.511*	1.000	-.498*
	Sig. (2-tailed)	.000	.247	.368	.137	.000	.388	.015		.018
R	*Correlation Coeffi.*	-.899**	-.294	.195	.092	.440*	-.009	-.359	-.498*	1.000
	Sig. (2-tailed)	.000	.184	.385	.685	.040	.968	.101	.018	

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

We could not establish a pattern between TC duration and changes in upper level divergence that we could use to predict the duration of a TC on land. We therefore resigned divergence to the unexplained variance of the regression model.

Assuming therefore that only two variables are dominant – surface roughness and central pressure – *Cp* at landfall averaged at 967 hPa. It is known that the wind speed is related to the central pressure (Knaff and Zehr 2007) and we are measuring duration with wind speed until it goes below a threshold value. The threshold value is 46 km/hr (10-minute interval) as mentioned in the Best Track database of BoM, which corresponds to Dvorak's (1975) intensity T1. We can therefore exclude *Cp* and, the only explanatory variable that remains and deserves further scrutiny is the surface roughness.

Table 3 Results from the principal component analysis.

Component	*Initial eigenvalues*			*Independent variables*	*Component*	
	Total	*% of Variance*	*Cumulative %*		1	2
1	3.246	40.572	40.572	*Lat*	-.862	.275
2	2.259	28.233	68.805	*Lon*	.793	.158
3	.871	10.891	79.696	*Rh*	.887	-.322
4	.643	8.042	87.738	*Cp*	.321	.849
5	.424	5.297	93.035	*Sms*	-.754	.385
6	.291	3.640	96.675	*Temp*	.136	-.723
7	.178	2.224	98.899	*Div*	-.494	-.634
8	.088	1.101	100.000	*R*	.392	.511

Determination of land surface roughness coefficient

The influence of orographic terrain on the intensity and movements of a landfalling TC has drawn considerable attention of researchers for some time (Miller 1964; Powell 1987; Bluestein and Hazen 1989). A primitive model has been developed to capture the influence of an orographic terrain on landfalling TCs in the study of Chang (1982). Bender et al. (1987) examined this effect in a numerical landfall simulation where an idealized mountain range was compared with flat shore. In our study, for the real-world scenario, a series of steps have been undertaken to quantify and refine the value of the surface roughness coefficient which can be used in predicting the duration of a landfalling TC.

First, we chose a number of TCs which are identified in Table 1 with non-italic names, and plotted for each TC the inverse of central pressure versus time in a semi-log graph. This is based on the fact that if $dv/dt \propto v$, where v is the wind speed; after integration we get a relationship of the form $\ln v = c_1 t + c_2$, where c_is are constants. Since v is closely related to the central pressure, we can compute v at $t = 0$ (at the point of landfall), and thus we get the relationship

$$\ln \frac{v_t}{v_0} = c_1 T \tag{4}$$

Where v_t is the termination velocity (which is actually a constant), v_0 is initial velocity and T is the duration. The coefficient c_1 is primarily due to the land surface roughness in our case, a semi-log plot is appropriate whose slope would yield the c_1 value. Put simply, the slope of the straight line that can be fitted to the points is an estimation of the surface roughness coefficient somewhat corrupted by other factors which contribute to a TC's decay. Since the other factors have been found to have no consistent significant relationships, it is unlikely to have a consistent significant component in the value of the slope. The presumption that underpins this analysis is that the surface roughness coefficient is proportional to the resistance experienced by a TC on land.

Second, to remove the effect of non-significant factors on these estimated values or, in other words, to refine these values, we worked with the regression model (2) for the duration. The initial run of the model produced a value of 0.68 for the coefficient of determination (R^2). For the next step in the analysis, we did a sensitivity analysis for each value on the coefficient of determination by introducing small perturbations in R (no more than 20 percent). The idea was that the values of the roughness coefficients that would contribute toward the maximum improvement of the R^2 would be retained. These roughness coefficients can be considered as true values; the process yielded a higher value of 0.76 for the coefficient of determination with equation (3).

Then, in an attempt to relate the roughness coefficients with the physical characteristics of the terrain, snapshots of terrain were taken from Google Earth. Two properties were considered, which are relevant to a TC's decay, to describe the terrain: forest coverage and degree of undulation. Values of these were estimated using the following relationships:

Forest coverage = ratio of tree canopy area to total land area in the vicinity of landfall.

Degree of undulation = ratio of actual distance along the surface on land between two points on a TC's path and the horizontal distance between these two points.

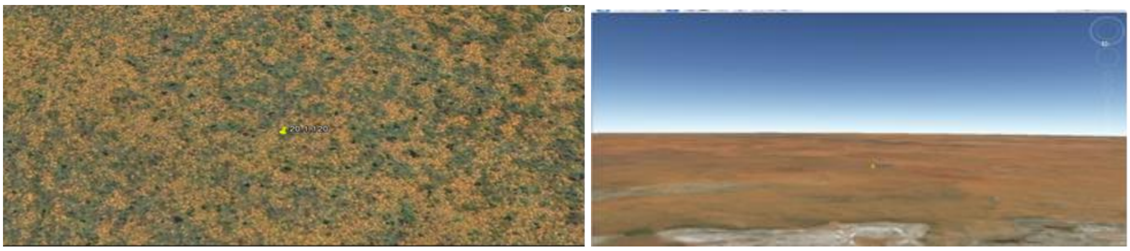
For a barren land or grassland with no trees, the forest coverage would be zero, and for a flat terrain with no hills, the degree of undulation would be unity. The other values determined for different types of "forest coverage" from the terrain pictures are according to Table 4.

Table 4 Assigned values of "Forest Coverage" for various types of forest in terrain snapshot.

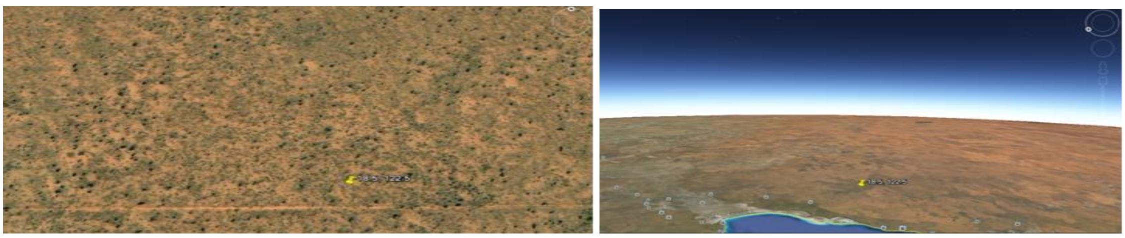
Type of forest coverage	*Our assigned values*
Barren land or grassland	0.00 – <0.05
Grassland with bush	0.05 – <0.15
Desert bush	0.15 – <0.25
Semi-dense tree forest	0.25 – <0.35
Dense tree forest	0.35 – <0.65
Rain forest	0.65 – <0.75
Deep rain forest	0.75 – <0.95

Figure 2 is snapshots from Google Earth to give a visual impression about forest coverage and degree of undulation. Where contour maps were available, we used those maps for additional information. But most landfall sites were in remote locations with no such information available.

Figure 2 Pictorial view of the terrain on the tracks of two TCs.



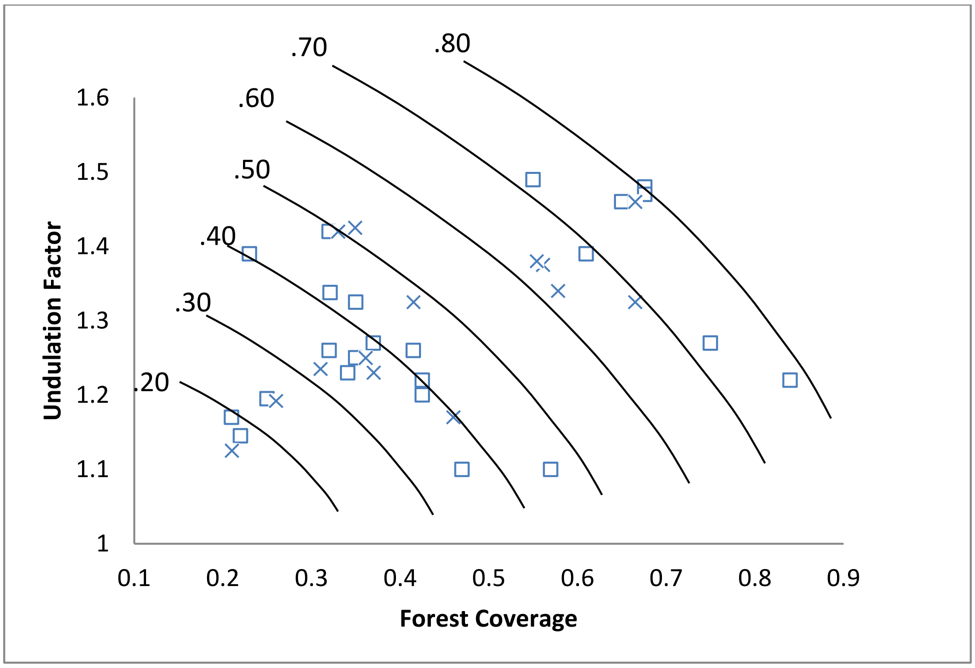
(a) Latitude 20.1^0S and Longitude 120^0E is on track of TC CHRIS (2002). Duration is 30 hours, forest coverage is 0.52, degree of undulation is 1.52 and roughness coefficient is 0.64.



(b) Latitude 18.5^0S and Longitude 122.5^0E is on track of TC ROSITA (1999). Duration is 27 hours, forest coverage is 0.35, degree of undulation is 1.43 and roughness coefficient is 0.52.

In Figure 3 we have plotted the surface roughness coefficient on a graph with the degree of undulation versus forest coverage. The scatter plot is shown for all the TCs considered in this study (square dots for model calibration and crosses for model validation), and over it, we have drawn smoothed contour lines for various surface roughness coefficients, which comes from equation (4) with adjustments. In the figure, we can notice the values of roughness coefficients are directly related to both of these terrain characteristics. As an example, for forest coverage of 0.40 and degree of undulation 1.1, the roughness coefficient will be 0.30. If the point of intersection of forest coverage and degree of undulation on the graph does not fall on a contour line, the method of interpolation can be used.

Figure 3 Graph presenting the values of surface roughness coefficient against land undulation factor and forest cover proportion. Each contour line identifies the roughness coefficient.



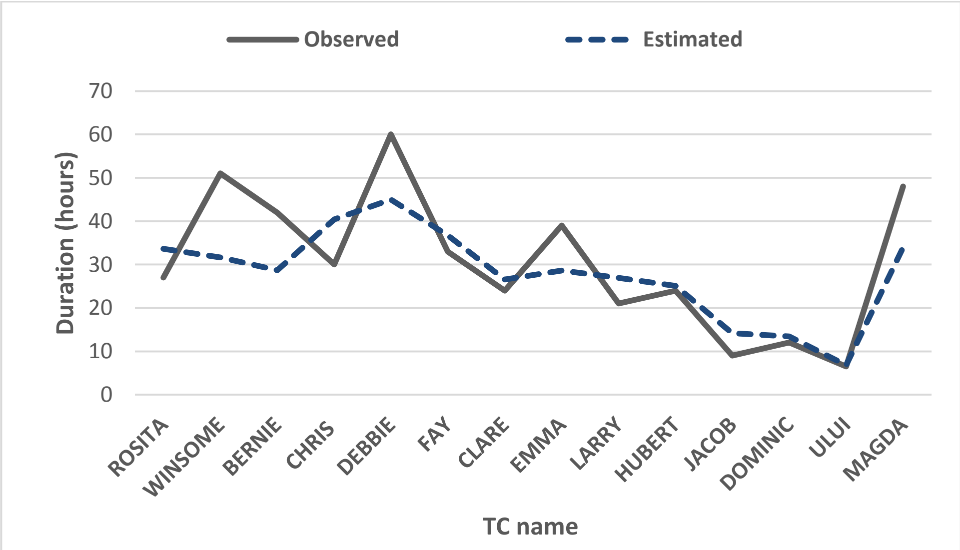
Usefulness of the surface roughness coefficient

One of the reasons that we focused only on land surface roughness earlier is that many of the factors identified in published literature have no continuing influence after the landfall event has occurred. However, to judge the usefulness of the surface roughness coefficient we resorted to the stepwise regression modelling technique starting with all the variables identified in published literature. Although three explanatory variables were identified in equation (1), for prediction purposes, equation (3) was found to be tractable without any significant loss of information. Ultimately, the only explanatory variable that stood out is the land surface roughness.

To verify the justification and usefulness of Figure 3 and to validate the model, we chose the remaining cyclones in Table 1 which were not selected for model calibration. We use the observed values of central pressure along with the estimated surface roughness coefficient from Figure 3 in the regression equation (3) to estimate the duration of the landfalling TC. Figure 4 compares the observed durations with the estimated durations. During the validation phase the R^2 value of the model was 0.59.

This R^2 value is rather low, but the value itself can be somewhat misleading in capturing a model's performance. It is not uncommon for models to be significantly off for extreme values, which highly affects the value of the coefficient of determination though the model could be performing well most of the time. Thus, to provide a visual impression of what happens with individual storms, comparison of observed and predicted values are provided in Figure 4 for the validation data.

Figure 4 Graphical presentation of observed and estimated TC durations after landfall using equation (3).



Considering the fact that cyclone movement prediction is a very imprecise science, Figure 4 captures the duration characteristic reasonably well. Furthermore, the validation process here is not interpolation; rather it is extrapolation, which gives more strength to our assertion of the usefulness of the model. The mean absolute deviation (MAD) for the validation phase is 7.8 hours. There is no pattern in the error values, which indicates a more complex statistical model is unlikely to be more useful. There appears to be some over-shooting of extreme values, which is not unusual in a statistical model.

Conclusions

The sojourn on land of a TC is of critical importance because it is when major catastrophes unfold. An attempt was made in this study to develop a statistical model based on the explanatory variables cited in literature for the duration of a TC on land. Further analysis of the model and a closer look at the variables revealed that the true explanatory variable, that has continuing influence after the landfall event occurs and has predictability properties, is perhaps only the land surface roughness. Since the determination of the numerical representation of surface roughness is difficult, we adopted a retrogressive approach to arrive at an estimate of land surface roughness from the observed TC data.

In the next stage of research, we attempted to relate the estimated land surface roughness with the physical features on land. The two physical features we chose are the type of ground cover and the degree of undulation of land. We believe that the proportion of forest coverage would directly contribute to resistance, and also, land undulations would create additional turbulence wasting the TC's energy. We established that is actually the case with the observed data in the Australian basin. We claim that relating land surface roughness to forest coverage and land undulations is useful for predicting TC durations on land.

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