A Physical Interpretation of Recent Tropical Cyclone Post Landfall Decay

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Key Points:

- A simple physically based vortex decay model of maximum surface winds was ultised to investigate post-landfall decay.
- The decay parameter obtained from the model has been decreasing from 1980 to 2018.
- A global mean increase of wind speed 24 hours after landfall is consistent with this slower decay.

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Abstract

The decay of landfalling tropical cyclones (TCs) is important to the damage caused. We examine a simple physically based decay model of maximum surface winds driven by frictional turbulent drag and a modification accounting for partial to complete land roughness. The model fits an algebraic decay with a parameter determined by the ratio of the surface drag coefficient to the effective vortex depth. This parameter has been decreasing from 1980 to 2018. There is also a global mean increase of wind speed 24 hours after landfall of +1.13 m/s per decade. We cannot exclude the possibility that this trend is driven by the initial wind speed increase, but it is most likely due to a slowing of the decay. This weaker decay amounts to an additional 7 hours of gale force winds for a typical Category 1 at landfall.

1 Introduction

The inland effects of major tropical cyclones (TC) can be devastating (Coch, 2020). An increase of inland risk is implied by recent trends of intensification over the ocean (Bhatia et al., 2019; Wang et al., 2020), coastal migration (Wang & Toumi, 2021) and slowing land decay (Li & Chakraborty, 2020). A combination of factors are thought to control the decay of TCs after landfall including the reduction of surface moisture fluxes and increased frictional dissipation from the rougher land (Chen & Chavas, 2020). A simple empirical exponential model of post landfall decay (Kaplan & DeMaria, 1995) has been widely used operationally within the Statistical Hurricane Intensity Prediction Scheme (SHIPS) (DeMaria et al., 2005), typhoon prediction scheme of Knaff et al. (2005) and the Southern Hemisphere Statistical Typhoon Intensity Prediction Scheme (SH STIPS) (Knaff & Sampson, 2009). In stochastic risk modelling the exponential model is also used Bloemendaal et al. (2020). In regional studies the exponential model has been applied to case studies for New England, USA (Kaplan & DeMaria, 2001), India (Bhowmik et al., 2005) and Southern China (Wong et al., 2008) landfalls. In a recent trend analysis, the exponential model was used to infer a recent slowing of land decay of hurricanes (Li & Chakraborty, 2020). Several refinements have been considered by including an adjustment to the initial landfall wind speed, consideration of islands (DeMaria et al., 2006) and a pressure filling variant (Vickery, 2005).

Despite the extensive use of the exponential model, an empirical model can only provide limited understanding of the decay problem. Furthermore, theoretical studies of the spin-down of geophysical vortexes by Greenspan and Howard (1963) and Eliassen (1971) have demonstrated that the exponential decay of the tangential winds is strictly only valid for a laminar boundary layer. Therefore the assumption of a simple exponential decay is questionable for TC environments with shear-driven turbulent flow (Montgomery et al., 2001). An alternative for a turbulent flow regime would be in the form first theorized by Eliassen (1971) and expanded in Eliassen and Lystad (1977), predicting an algebraic temporal decay. This theory was later validated by Montgomery et al. (2001) for modelled hurricane strength vortexes over the ocean. Smith and Montgomery (2008) and Vogl and Smith (2009) cast doubt over some of the linearity assumptions. Nevertheless the simplicity of the analytic model is attractive to provide a physical interpretation of the observed TC decay over land. Here, we examine, for the first time, this decay model against global landfall data, propose a modification and finally find recent changes in observed post landfall wind speeds.

2 Methods

2.1 Decay Models

The algebraic decay model (ALG) is based on quadratic form of the turbulent drag;

$$\frac{dv}{dt} = -Kv^2 \tag{1}$$

with the solution;

$$\frac{1}{v_t} = \frac{1}{v_0} + Kt \tag{2}$$

where v_t is the maximum tangential surface wind speed at some time t, v_o is the initial tangential surface wind speed at landfall ($t = 0$) and K is the decay parameter defined as;

$$K = \frac{C_D \chi}{H} \tag{3}$$

where C_D is the surface drag coefficient, χ is the ratio of tangential winds at the surface to the top of the boundary layer. H is the effective height of the vortex and refers to the depth of over which the friction acts to spin down the vortex. The half life can also be found from Eq. 2;

$$t_{1/2} = \frac{1}{v_0 K} \tag{4}$$

where $t_{1/2}$ is the time to half intensity from initial maximum wind intensity (v_0). The decay parameter, K, determines the rate of the decay. A rougher surface (large C_D) increases the rate of the decay while a larger depth, H, decreases the rate of decay. This is physically sensible as a rougher surface causes more friction and a larger effective vortex height would take longer to spin-down.

K may increase during the transition from ocean to land because C_D can be expected to increase. During the early stages of landfall, C_D transitions from lower values over the smoother ocean to higher values over rougher land. This transition is however not instantaneous with some proportion of the cyclone remaining over the ocean at landfall. The exact values of C_D, χ and H for transitioning to over land are unknown for each individual case. In this framework H stays the same as the wind speed decays, representing an average H during the decay within the model fitting. In reality H may also decrease. It is also difficult to quantify any change in χ for the transition.

DeMaria et al. (2006) suggested that the decay is slower if a portion of the storm remained over the ocean and accounted for this transition by modifying the exponential model of (Kaplan & DeMaria, 1995). Here we account for changes in turbulent drag over the ocean and land. Therefore, assuming the same symmetry at landfall ($t = 0$) half of the the cyclone is over the ocean. We then assume that the initial decay parameter K is only half ($K/2$) of it's final value K at some time t_s when the entire cyclone is fully over the land. We do not set t_s as a function of radius and translation speed and instead allow t_s to become an extra parameter to be fitted. This means we do not need the radius which is rarely observed. K is set to relax exponentially from $K/2$ to K over this transitional timescale t_s. For the case of a landfalling TC the modified decay model (ALG-t) becomes;

$$\frac{dv}{dt} = -K(1 - \frac{1}{2}e^{-t/t_s})v^2 \tag{5}$$

with a solution;

$$\frac{1}{v_t} = \frac{1}{v_0} + Kt + \frac{Kt_s}{2}(e^{-t/t_s} - 1) \tag{6}$$

where t_s is the transitional time scale. The half life is similar to Eq.4 but with a small additional term. Increasing the transitional time scale reduces the initial decay and gradually relaxes the decay rate to that of the original model, imitating the effect of the TC gradually moving over land. We also compare both the ALG and ALG-t models to the exponential model (EXP) formulated as a linear drag;

$$\frac{dv}{dt} = -\alpha v \tag{7}$$

and exponential decay,

$$v_t = v_o e^{-\alpha t} \tag{8}$$

where α is the decay constant and $\tau = 1/\alpha$ is the decay time constant.

2.2 Data

The models are applied to the global International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010, 2018) data. Starting from the IBTrACS data (for consistency we only utilise data from the USA agencies) the tracks are linearly interpolated to hourly resolution and verified to be over land (Hastings et al., 1999). We only consider storms that are at least Cat 1 ($v_0 > 33$ m/s) at landfall over a continental landmass and are recorded for at least 24 hours over land. We only consider storms that decay and do not re-intensify. We also include 6 storms that reached peak intensity within 6 hours post landfall. With this criteria 131 TCs were available for this analysis (see Fig. S1). The 24-hour decay is then fit to each model using non-linear least squares at 6 intervals (00, 06, 12, 18 and 24 hrs at/after landfall) as in Li and Chakraborty (2020) to obtain the algebraic decay parameter K, a transition timescale t_s, and the exponential decay constant α.

3 Results

3.1 Model Performance

The average decay of the maximum wind speed over land is shown for the standard algebraic decay model (ALG, Eqn. 2), modification (ALG-t, Eqn. 6), exponential decay model (EXP, Eqn. 7) and best track observations in Figure 1. While Figure 1 suggests a better mean performance for the exponential model, Table 1 shows that ALG-t has a lower mean absolute error than the exponential for most hours during the decay. The addition of a time-varying K over some timescale t_s (ALG-t) reduces the errors and bias of the original ALG model. The mean Pearson correlation (r^2), time-averaged mean absolute error (MAE), root-mean-squared error (RMSE) and 6-24 hr mean bias or mean absolute error are also shown in Table 1. The average values of the fitted parameters for each model are; K = 4.22 x 10^{-7} m−1 (ALG), K = 5.24 x 10^{-7} m−1, t_s = 7.4 hrs (ALG-t) and α = 0.044 h−1. Storms with $t_s > 1$ hr have a mean t_s = 9.5 hrs. This is consistent with the average translation speed over land (20 km/hr) and radius of gale force wind (200 km), which gives a transitional timescale of 10 hrs.

Overall, the performance of the physical and exponential models are similar. However, the ALG and EXP models do differ in their dependence on the initial wind speed v_0 at landfall (Fig.2). We find a positive relationship between the initial landfall v_0 and the value of decay constant α for each storm (r^2=0.08, $p<0.01$). However, the algebraic decay parameter, K, does not depend on v_0 (r^2=0.02, $p>0.05$).

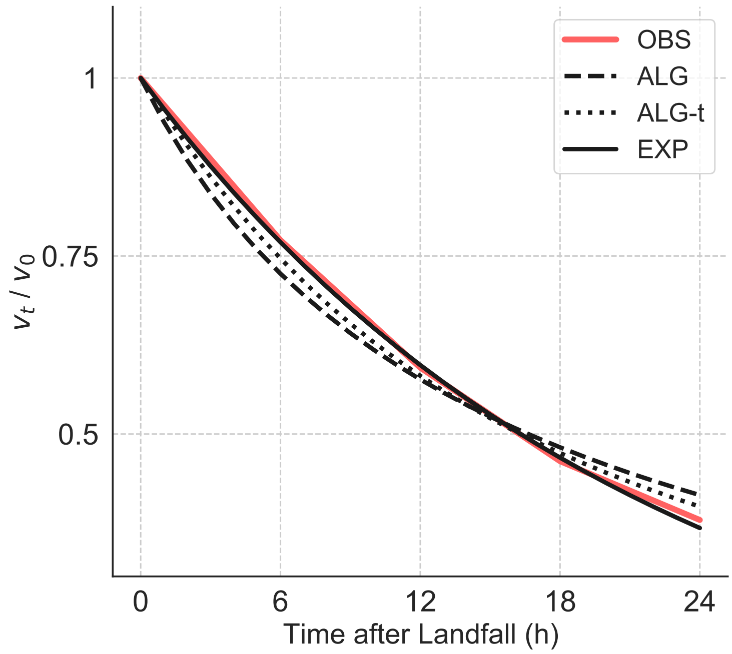

Figure 1. The global average maximum speed as a function of time post landfall normalised by the initial maximum speed (v_t/v_0). Observed speed from best track data set, OBS (red solid line); the fitted algebraic model, ALG (black dashed line), the modified algebraic model, ALG-t (black dotted line) and exponential model, EXP (black solid line)

Table 1. Average correlation and model error of v_t in m/s. The mean Pearson correlation (r^2), mean absolute error (MAE), root-mean-squared error (RMSE) and 6 to 24 hr mean bias (absolute error) for the standard algebraic (ALG), modified algebraic (ALG-t) and exponential (EXP) model.

Model	r^2	MAE	RMSE	Mean Bias (Abs. Err.)	6h	12h	18h	24h
ALG	0.96	1.5	1.9		-2.2 (2.6)	-0.7 (1.4)	0.9 (1.3)	1.6 (2.2)
ALG-t	0.97	1.1	1.4		-1.2 (1.7)	-0.5 (1.2)	0.5 (1.0)	0.9 (1.6)
EXP	0.97	1.1	1.4		-0.2 (2.0)	0.2 (1.4)	0.2 (0.9)	-0.5 (1.9)

3.2 Trends

Long-term trends of estimated K, t_s and α for each storm from 1980 to 2018 can also be examined. K exhibits a negative global trend of -0.35 ± 0.31 x $10^{-7}m^{-1}$ and -0.42 ± 0.37 x $10^{-7}m^{-1}$ per decade for ALG (Figure 3a) and ALG-t respectively ($p< 0.05$). This shows that land falling major cyclones are decaying more slowly globally.The transitional time scale t_s of the ALG-t model fit remained unchanged at around 7 hours (not shown). The EXP model exhibits no global trend in the exponential time constant (Figure 3b). For North Atlantic (USA, Mexico, Central America) hurricane and China typhoons landfall we do not find a significant decrease in either exponential or algebraic decay constants (not shown).

Figure 4 shows the trends of observed maximum surface wind speed at landfall and 24 hours later. For the wind speed at landfall, v_0, a nearly significant trend of $+1.54 \pm 1.54$ m/s (p=0.05) is found. The wind speed further inland (v_6,v_{12},v_{18},v_{24}) has also been

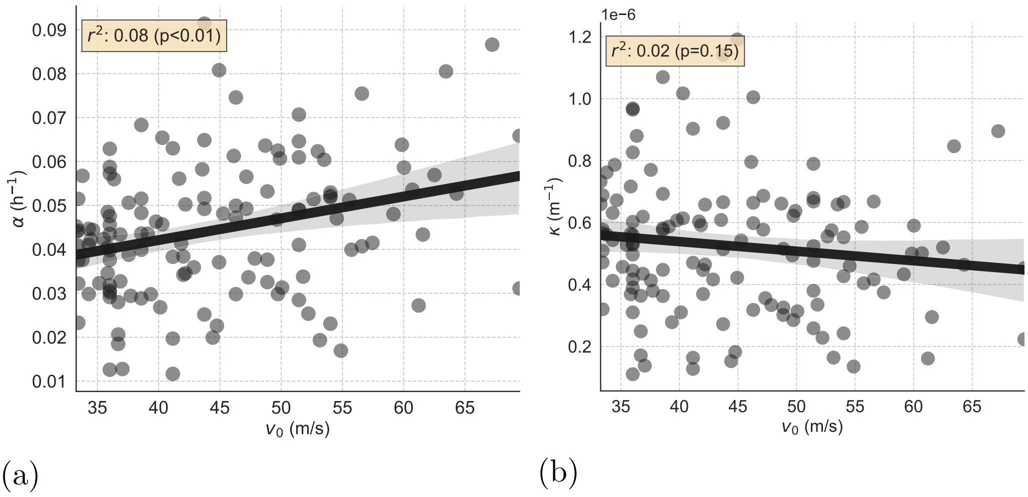

Figure 2. Dependence of decay parameters on the initial wind speed v_0 for a) the exponential decay constant α and b) the algebraic decay parameter K. A linear regression for each is highlighted as a solid line.

increasing. We find that the wind speed trend has the smallest error at 24 hours and has been increasing by 1.13 x ± 0.92 m/s per decade (p=0.02). This global average increase in v_t further in land is consistent with the decrease in the decay parameter,K found earlier (Fig.3a).

Globally averaged trends are significant only after landfall (Fig 5a). Three countries together make up the majority of land falling events in the data: the USA, China and Australia. Wind speed increases are found at all times except in Australia. However, the significance depends on the time after landfall. For the USA the trend for the wind speed becomes significant at the end of decay at 24 h (Fig 5b). For China significance is only found at landfall (Fig 5c).

4 Discussion

We analysed the global decay of tropical cyclones post landfall. The statistical performance of the physically based algebraic model of TC decay and a small correction for the ocean to land transition perform statistically very similar to the widely used empirical exponential model. This is the first time decay models have been compared for a global data set and highlights that the algebraic model could enable a physical interpretation of post landfall TC wind speed evolution.

Kaplan and DeMaria (1995) showed that the exponential exponent depends on the initial value. This has been confirmed by subsequent studies in the USA and elsewhere (Kaplan & DeMaria, 2001; Bhowmik et al., 2005; Wong et al., 2008). We also find that the correlation of an exponential decay coefficient with v_0 globally is small but significant. Similar correlation coefficients were found by Wong et al. (2008) for the South China. However, this behaviour is mathematically inconsistent with a proposed simple exponential decay, which requires a time constant independent of the initial value. Empirical adjustments that are frequently applied to correct for this are thus a recognition of this model's inadequacy. This is perhaps not surprising as theoretically an exponential model would be appropriate for laminar boundary layer, but for TC eye wall conditions a turbulent

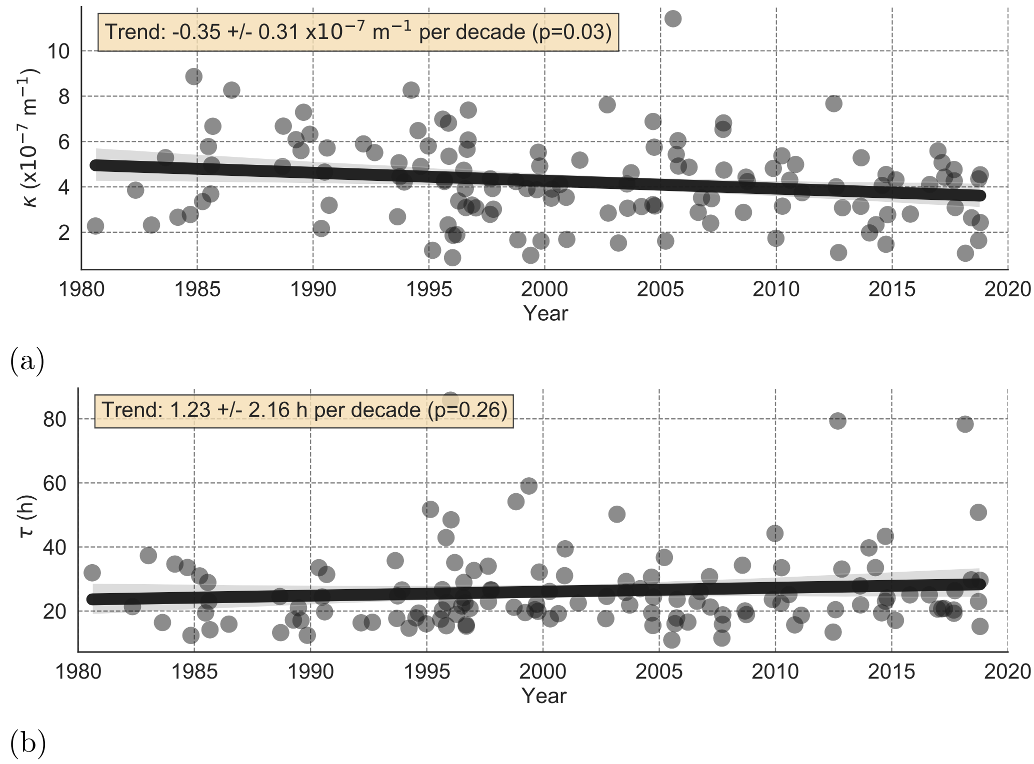

Figure 3. Time series of the decay parameters for each landfall (1980-2018) with a linear regression line, trend and p-value in the figure: a) the ALG decay parameter K (m^{-1}); b) the exponential time constant τ (h) (=1/$alpha$).

layer is much more plausible. Turbulent surface drag underpins the algebraic decay model. In our framework the algebraic decay parameter K does not depend on the v_0.

The decay parameter K is essentially controlled by the ratio of two physical quantities: the surface drag co-efficient and the effective vortex depth which is being spun down. The land surface drag coefficient is very uncertain. This is partly due to the complexity of land surface, but there is also evidence of a decreasing drag coefficient for increasing wind speed and increased instability (Srivastava & Sharan, 2015). They suggest that the drag coefficient at 10 m/s for tropical convective conditions could be about 3.0 x 10^{-3}. Is the algebraic model consistent with a reasonable estimate of an effective vortex depth ? For a global mean value of K of about 5 x $10^{-7}m^{-1}$, $\chi\ =\ 0.8$ (Powell, 1980), and a $C_D = 3$ x 10^{-3} then an effective vortex depth, H, of about 5 km would be inferred. This crudely estimated height is at least plausible as the depth over which the vortex is spin down given all the uncertainties and simplifications. H may approximate to half the height of the tropopause or the height of half-maximum v_0 and could remain constant during the decay. The advantage of the algebraic model over the empirical exponential decay is that because it has a physical framework the relevant physical variables can be interpreted. A full physics model will capture more details of the boundary layer and its parameterisation (Zhang & Pu, 2017; Zhang et al., 2021).

We find a decrease in observed global average post landfall decay. For example, a tropical cyclone with $v_0 = 33$ m/s (Cat 1) in the 1980s would have a half life (time to decay to 17 m/s i.e. a gale force strength wind) of around 16 hours. By now this Cat 1 storm would have a much larger half life of 23 hours. This increase could amount to

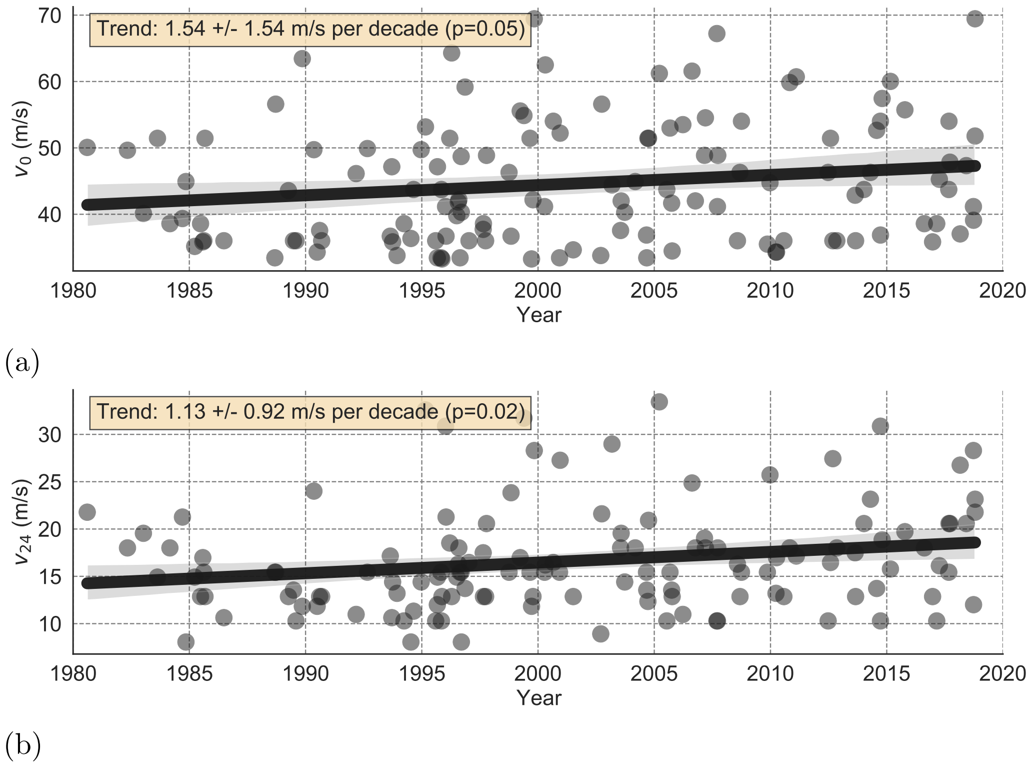

Figure 4. Time series of v_t (m/s) of each landfall event globally (1980-2018) with a linear regression line, trend and p-value for a) v_0; and b) v_{24}; .

much more damage in land with an extra 7 hours of gale force winds. It is interesting to note that under the algebraic framework the half-life decreases with more intense initial landfall intensity (Eqn. 4). There is an element of self-regulation: in-land wind speed changes are mitigated by the shorter half-life of any potential increase in initial landfall intensity (Wang et al., 2020).

This is the first time a global average trend in landfall decay is presented. For North Atlantic (USA, Mexico, Central America) hurricane landfall we do not find a significant decrease in either exponential or algebraic decay constants. This appears to be in disagreement with the recent study of Li and Chakraborty (2020). However, if we adopt their criteria and allow storms that re-intensify after an initial decay we do then also find a trend in the exponential time scale of $+5.0 \pm 4.7$ hr per decade (p=0.04) and this agrees with their 3 hr/decade trend. Re-intensification appears to explain a large part of their trends. For landfall in China we find no change in algebraic decay parameters or exponential time constant. This is consistent with the lack of trend of the weakening rate over the same time period as reported by Liu et al. (2020).

The wind speed at different times post-landfall is increasing by about 1 m/s per decade on average globally. An analysis of three countries which account for most of the global landfall shows differences between them. There is no significant change in Australia. Although there is an increased wind speed at all times for the USA and China, the significance depends on the time post landfall. The small sample size makes it difficult to detect trends at country level.

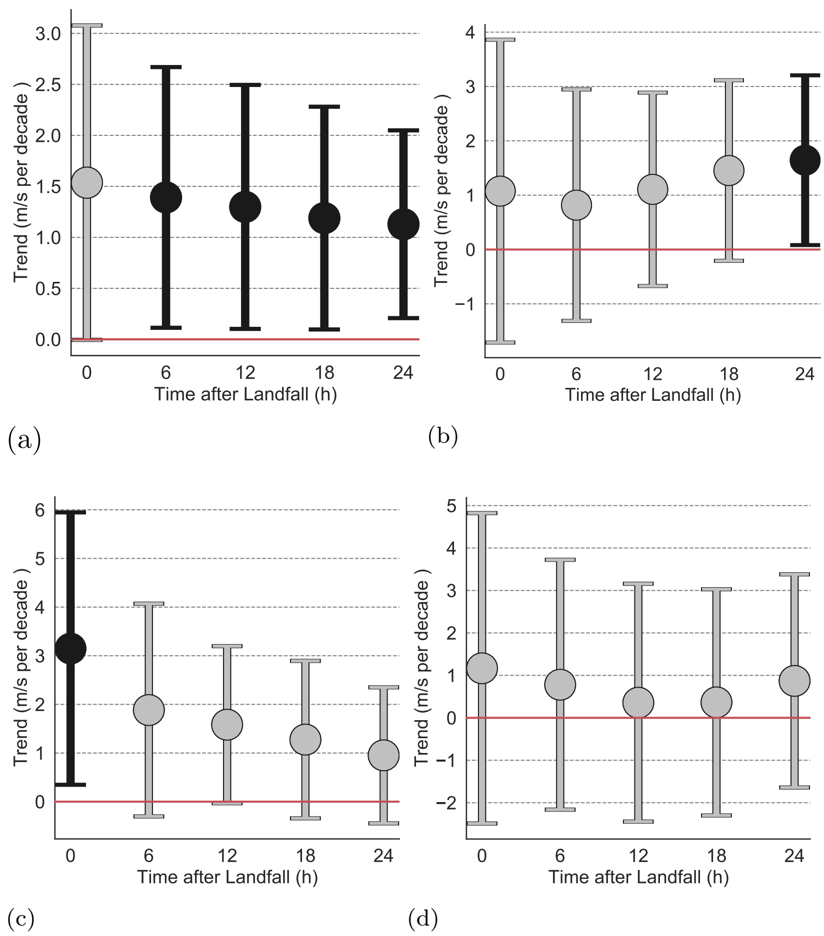

Figure 5. Global and country v_t trends (m/s per decade) with 95% confidence intervals for different times (0-24hr). The trends highlighted in black indicate significance at p=0.05. The zero trend marker is highlighted as a solid red line. a) Global (131 events). b) USA (29 events). c) China (32 events). d) Australia (27 events).

Is the v_{24} increase mostly driven by the v_0 at landfall or the decay parameter? If we assume no change in v_0 and the observed trend K of -0.35 ± -0.31 x $10^{-}7$ per decade then, according to Eq .2 the v_{24} trend would be +0.92 ± 0.84 m/s per decade and thus close the observations (+1.13 ± 0.92 m/s per decade). However, for no change in K and assuming a v_0 trend of +1.54 ± 1.54 m/s per decade this would produce a trend of v_{24} of +0.56 ± 0.56 m/s per decade, still within the error of the observed v_{24} trend. We can therefore not exclude the possibility that the inland trend is caused by a change of v_0, but our best estimate (smallest error in trend) is that it is the slowing decay that is responsible.

Li and Chakraborty (2020) attribute enhanced atmospheric moisture from ocean surface warming as the cause of the slowing decay of hurricane land decay. In our framework enhanced moisture could slow the decay by increasing H through enhanced latent heating in the eye wall. Komaromi and Doyle (2017) report a strong positive relationship between outflow potential temperature (a measure of height) and the mean equivalent potential temperature of the boundary layer inflow. Recent moisture enhancement could thus have lead to either stronger v_0 or larger H. However, the physical framework identifies v_0 and H as two different variables that are not necessarily always linked.

5 Conclusion

We have shown that a simple, physically based, decay model can be useful for modelling the decay of tropical cyclone post landfall. We propose a small modification that accounts for the land roughness increase during the cyclone movement from partially to fully over land. The empirical exponential decay model, widely utilised for tropical cyclone land decay studies, does not perform much better than this physical interpretation, but does have some theoretical and practical limitations. Observations show a recent increase in wind speed post landfall and a longer time of gale force winds over land. We can not exclude the possibility that this is due to increases in intensity at landfall, but our best estimate is that the in-land increased wind speed is due to a slowing of the decay.

Acknowledgments

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