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Do mangroves provide storm protection from wind damages of a storm?

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Abstract

Earlier research demonstrates that mangroves provide storm protection in terms of saving lives and properties by buffering the impacts of storm surge. We provide theoretical and empirical evidence that mangroves also attenuate damages from strong winds and provide substantial protection to properties even relatively far away from mangroves and coast. We show empirical evidence that areas with mangroves protection in the Orissa region in India experienced significantly less damages from the 1999 cyclone compared to areas without mangrove protection. In addition we theoretically model mangroves' wind protection. Model simulations using data from the same cyclone show that our model could predict the actual level of damage to a large extent.

Key Words: Ecosystem Services; Orissa; Mangroves; Storm Protection; Wind Protection

Do mangroves provide storm protection from wind damages of a storm?

1. Introduction

Storm protection services of mangroves like attenuating storm surges and protecting the hinterland from excessive storm impacts are well established for some coastal areas (Das & Vincent, 2009; Barbier et al., 2008; UNEP-WCMC, 2006). There is also theoretical evidence of the mechanisms underlying wave attenuation that mangroves provide (Mendez & Losada, 2004; Mazda et al.2003, 1997; Massel et al., 1999; Kobayashi et al., 1993). However, it remains unclear whether mangroves reduce wind damages inflicted by storms or not. We hypothesize that mangroves could act as wind barriers even for areas hit by the tangential (or radial) wind[1] outside the eye of a cyclone.

Tangential wind of storms move in anti-clock direction around the storm centre (in Northern hemisphere) and the maximum wind in the eye area determine its potential velocity at different radial distances. The velocity of maximum wind decrease exponentially after the landfall because of reasons like interaction of cyclone with rough surface, reduced moisture supply due to being away from the sea, conversion of heat in the form of rain, etc. (Singh and Bandyopadhyay, 2005; Kalsi, *et. al*., 2003; Kalpana and Demaria, 1995; Basu and Ghose, 1987; Dube, *et. al*., 1981). Likewise, we would expect radial wind velocity also to decrease as it encounters rough space on its path. Theoretically radial wind velocity is assumed to be the same on a circle surrounding the eye wall, but in reality wind damages tend to be larger near the coast and decrease as one goes inland even on the same circle. We also assume mangroves as wind barriers as its multi level canopy cover can help reduce wind velocity. In that case, the wind inflicted damages for villages in leeward side of the forest should be lower compared to villages facing the same wind velocity but with no mangroves in between them and the coast.

We propose to test two hypotheses, (i) the tangential wind velocity declines compared to the potential wind velocity as it moves away from the coast and (ii) wind barriers on the coast, like mangroves, increase the rate of decline of tangential wind. To test our hypotheses we use theoretical and empirical methods. We analyse wind damage data of a 1999 storm that hit the State of Orissa in India. We match actual damages with expected damages corresponding to the potential wind speed and examine the change in damage as one move away from the coast. We use econometric and simulation approaches and find that mangrove areas have lower wind damages compared to non-mangrove areas and the actual damages are lower than expected. First, we build a theoretical model of storm damage occurrences and then describe the study area, data used, results from econometric and simulation analysis. We finally present a brief conclusion of the study based on the results.

2. Model of Storm Damages

[1] There are two types of wind in a storm structure, i.e. maximum wind (called V_{max}) and radial or tangential wind. Maximum wind is the wind speed witnessed over the eye wall region (few km surrounding the eye of the storm) of the storm whereas radial wind is the wind speed beyond the eye wall and at different radial distances from the center of the eye of the storm. Maximum wind is dependent on the air pressure at the cyclone eye and radial winds are dependent on the maximum wind.

Cyclonic storms have a particular horizontal structure that consists of the eye, eye wall, spiral rain band and outer storm area (IMD, 2000). Storm impact differs in these areas. Villages falling under the eye and eye wall receive the strongest impact followed by villages of spiral rain band. The impact on outer storm area is too low to cause damage. We develop a model for a village in spiral rain band and then modify it for other areas.

In Figure 1, point A represents storm landfall and C, a village north of the landfall where it is meaningful to measure wind protection of mangroves[2]. Coastlines are nonlinear so maximum storm surge and wind typically hit a particular village from two different points on the coastline. Radial tangential wind follows a fixed direction and path whereas the surge enters the village from the minimum distance (these two points will coincide if the coastline is a straight line). The wind hitting village C enters the village from the coastal point (D) which is located at the same radial distance away from the landfall point as the village. Hence d = AC = AD is the radial distance from the cyclone eye to village.[3] To reach the village, the wind travels distance c = CD.

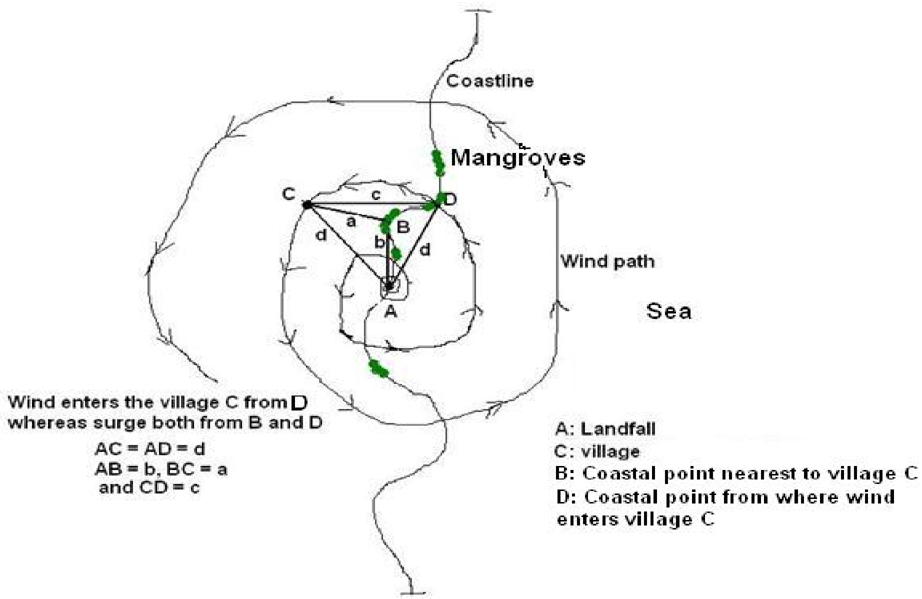

Figure 1: Model of storm damage

In contrast storm surge is expected to reach the village from the point on the coastline that is closest to the village (B). Distance a = BC represents the minimum distance between the village and the coast and b = AB is the radial distance from the storm landfall to the point on

[2] As storm wind moves anticlockwise in northern hemisphere, it is only in villages to the north of landfall that the wind direction will be from sea to land and the wind would pass through the mangroves before reaching the villages. So wind protection of mangroves can be measured accurately if the sample villages are located to the north of landfall, not to the south.

[3] In the above diagram, we show the wind moment of the cyclone by a spiral in which case AC ≈ AD = d. However, meteorologists approximate this spiral moment by a series of circles to measure wind velocity at different radial distances and thus assume AD = AC = d.

the coast that is closest to village C. By definition, $a \leq c$. Of course storm surge will also reach the village from point D and we assume storm damages to be proportional to the maximum surge impact from each of these points.[4] Let c^* denote the maximum distance that storm surge can cause damage. Hence if $c < c^*$, the village will suffer from storm surge and wind damages while if $c \geq c^*$ the village will only suffer from wind damage.

2.1 *General model: Village with storm surge and wind*

The percentage of houses getting damaged (*Y)* at a particular village depends on wind velocity (*V*) and velocity of storm surge (*W*).

$$Y = f(V, W) \qquad (1)$$

Actual wind velocity *V* over the village depends on the potential radial wind *R* and the reduction in wind velocity due to wind barriers *(WB)* on the path of the wind. Given the maximum wind velocity (V_{Max}), the radial distance from storm landfall to the village (*d*), the radius of the cyclone eye (*r*) and the decay parameter of radial wind velocity across radial distances of spiral rain bands μ, equation (2) provides a reasonable expression for the potential radial wind *R(d)* (Blanchard and Hsu, 2005; Roy Abraham, *et. al*., 1995; Das, *et. al.,* 1974).

$$R(d) = V_{Max}(\frac{d}{r})^{-\mu} \qquad (2)$$

Equation 2 gives the potential velocity of radial wind. We expect the actual wind velocity at a specific village to differ from the potential velocity as the wind comes from the direction of the coast and faces wind barriers on the way. We expect the coastal distance *c* and mangrove width *m* to be the only wind barriers that decrease the potential velocity to some extent.

Let the potential velocity of radial wind given by eq.2 decrease exponentially at the rate λ for every km distance it moves inland and additionally at the rate of δ for every km of mangroves it crosses on the way. The village is *c* km away from the coast. The distance m_1 denotes the mangrove width in this distance. Thus, equation (3) gives an expression for the reduction in wind velocity because of the barriers.

$$WB(c, m_1) = e^{-(\lambda c + \delta m_1)} \qquad (3)$$

Equation (4) provides then an expression for the actual wind velocity of the village.

$$V\left(d, c, m_1\right) = v(R(d), WB(c, m_1) = V_{Max}(\frac{d}{r})^{-\mu} e^{-(\lambda c + \delta m_1)} \qquad (4)$$

The velocity of storm surge, *W*, at this location depends on the sea elevation at the nearest coastal points S_b , sea elevation at the point from where wind enters the village S_d, and the

[4] Suppose sea elevation at B is S_b and at D is S_d and c > a. If B is to the south of D or more closure to landfall, then $S_b > S_d$ and surge will reach faster from point B and surge impact from this point will be higher. However, if B is to the north of D, then $S_b < S_d$ and in spite of B being closure to the village than D, the surge may reach faster from point D and may cause higher impact.

surge barriers present in between these points and the village.[5] Along with storm surge, the height of astronomical tide also matters for sea elevation. Thus S_b and S_d denote the sum of the heights of sea elevation and astronomical tide. Again coastal distance and mangroves are assumed the only surge barriers (*SB).* We assume the storm surge height to decrease at an exponential rate of α per km of distance it travels inland[6] and by the rate of η per km of mangroves it crosses. Thus equation (5) provides the decline in surge height after it travels *c* km passing *m* km of mangroves on its way to the village.

$$SB(c,m) = e^{-(\alpha c+\eta m)} \qquad (5)$$

Equation (6) gives the storm surge height (or the surge velocity, W) at a village facing surge height S_d at the point from where wind is entering the village, height S_b at the nearest coastal point and these two points are *c* km far with m_1 km of mangroves and *a* km far with m_2 km of mangroves respectively.

$$W(S_d, S_b, a, c, m_1, m_2) = \max\left\{S_d e^{-(\alpha c+\eta m_1)}; S_b e^{-(\alpha a+\eta m_2)}\right\} \qquad (6)$$

Wind damage to houses is proportional to the square of wind velocity (Pielke *et.al.* 2003; Farber, 1987). Similarly and based on private consultation with meteorologists, we assume house damage by storm surge to be proportional to the square of storm surge velocity, which is proportional to height of storm surge[7]. So the house damage because of storm surge is assumed proportional to height of storm surge over the village. Some meteorological literature links different wind velocities and expected damage to structures, but we found no information on links between levels of storm surge and house damage. Hence we convert the damage potential of storm surge heights over villages to equivalent wind velocities. Let W_e denotes the equivalent wind measured as a function of storm surge height *W* expressed in (6). We assume that the house damage can be expressed as in equation (7).

$$Y = \beta\left[V_{Max}\left(\frac{d}{r}\right)^{-\mu} e^{-(\lambda c+\delta m_1)} + \{W_e\{\max(S_d e^{-(\alpha c+\eta m_1)}; S_b e^{-(\alpha a+\eta m_2)})\}\}^{\frac{1}{2}}\right]^2 =$$

$$\beta\left[V(d,c,m_1) + \{W_e(S_d, S_b, a, c, m_1, m_2)\}^{\frac{1}{2}}\right]^2 \qquad (7)$$

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[5] Sea elevation due to storms is a complex process. Along with wind velocity, it also depends on multiple of other factors like the direction (inclination) of the cyclone at landfall, radius of maximum wind, local offshore bathymetry, inland topography, density of sea water, cyclone speed, height of astronomical tide, etc (Kalsi, *et. al*, 2004). However, for most of the coastlines, scientific models have been developed that can simulate the expected sea elevation correctly during the landfall of different storms and thus, sea elevation can be measured at a specific point at the coast.

[6] Waves, after they break at the coastline are seen to be decreasing exponentially as they move inland. They generally diminish in depth by 1 to 2 ft (0.3 to 0.6m) for every mile (1.6km) that it moves inland and a strom surge of 6m is expected to reach a maximum of 11 to 16km inland (Pielke et al., 2003). At our study area, the peak surge was 6m and surge inundation was reported to be as far as 30km inland. Using these data, we tried different functional forms and an exponential decline looks to explain the damages better.

[7] In storm surge inundations, the potential energy of water gets converted to kinetic energy. As per the energy conversion rule, potential energy is equal to kinetic energy or $mgh = \frac{1}{2}mV^2$ (m is mass, g is gravity, h is height and V is velocity) $\Rightarrow v^2 = 2gh$. Hence, V^2 is proportional to h (height), as gravitation is same for all villages. In the present case, V^2 is square of storm surge velocity and h is height of storm surge or sea elevation above the surface level which is a measure of amount of water piled up on the coast.

The surge height over each village (as defined in equation 6) is converted to equivalent wind velocity W_e and then, the square root of equivalent wind is added to actual wind velocity over the village to measure the combined stress on houses because of wind and storm surge. We added the square root of equivalent wind to actual wind velocity as house damage is proportional to the square of wind velocity and to storm surge height (not its square). Equation7 fits a village in the spiral rain band of storm structure and located at a distance *d* from the landfall, a distance *c* from the coastline from where wind enters the village, and a minimum distance *a* from coast (a < c) from where the surge is likely to enter the village first. This general equation fits villages with mangroves in the path of wind and storm surge. The equation can be modified to explain house damages for other villages not having any barrier, or having more than one barrier, facing only wind with no storm surge or located in other storm areas as shown later.

2.2 Simulation approach

We use equation (7) to test whether mangroves provided wind protection to houses or not in the area of study. We parameterize the equation using parameter values specific to the Orissa region studied and calculate the expected average house damage in different villages. We then compare these expected values with data on the actual house damages that where collected on site and assess the prediction accuracy of our model. To convert storm surge height into wind velocity equivalent we used the data on wind velocity and associated storm surge heights of different tropical storm categories as given by the Saffir-Simpson Hurricane Scale (see appendix table 1). Using this information, we got the following (best fit) equation for wind velocity and surge height and converted surge height to equivalent wind velocity:

$$wind\_velocity = 71 + 49.17(surge\_height) - 2.97(surge\_height)^2 \quad (8)$$

We link house damages to wind velocity using information on expected damage to structures during storms as given by Indian Meteorological Department (see appendix table 2). No damage is expected to thatched huts or *kutcha* structures (non-engineered structures with local construction materials) if wind speed is less than 62 km/h and catastrophic damage are expected if the speed exceeds 222 km/h. The study area was dominated by *kutcha* structures and areas witnessing wind speed 256km/h during the storm had been completely devastated. Using 248km/h (which is a multiple of 62) as the wind speed limit that bring 100% damage to non-engineered structures and less than 62 to cause zero damage, we linked up the wind speed and the corresponding expected percentage of damage to houses (Y') by formula (9).[8]

$$Y' = 6.2 * \left(\frac{wind\_velocity}{62} \right)^2 \quad (9)$$

Using (9), we calculate the expected damages to *kutcha* structures corresponding to different range of wind velocities, which are multiples of 62 and describe them in Table 1. We expect villages facing wind velocity in the range of 62 – 78 km/h to witness 6-10% of the houses

[8] Percentage of houses destroyed corresponding to 248kmh^{-1} wind speed = 100% and 248 = 62*4. So percentage of house destroyed at 62kmh^{-1} wind speed = [100 / (4^2)] % = 6.2%.

getting damaged and the ones with wind velocity 78 – 93km/h to have 10 – 14% of houses being damaged, etc. We compare these expected damage categories to actual damages witnessed in the study area villages in the simulation exercise.

Table 1: Wind categories and expected damage to *kutcha* structures

Range of wind velocity as multiple of 62 (=62*x) in kmh^{-1} (x = 1.25, 1.5, 1.8, 2, 2.25, 2.5,....3.8, 4)	Expected damage to *kutcha* structures (= $6.2*x^2$) in %.
62 – 78	6.2 - 10
78 – 93	10.15 - 14
93-112	14 - 19
112 – 124	19.2 - 25
124 – 140	25 – 31
140 - 155	31 – 39
155 – 176	39 – 49
176 – 186	49 – 56
186 – 201	56 – 65
201 – 217	65 – 76
217 – 236	76 – 90
236 – 248	90 - 100

The value of the parameters, the sources of value and the procedure of their measurement are discussed in result section.

2.3 Econometric approach:

To complement the results from our model simulation we also take an econometric approach to find out whether mangrove is significantly correlated with house damages that were caused mainly because of wind. To do so we estimate econometrically the relation between the number of damaged houses in village *i* (Y_i) with total number of houses (P_i), wind velocity (WV_i), mangrove width (M_i), coastal distance (CD_i) and storm surge (SS_i) as represented in equation (10) where ε represents the error term.

$$Y_i = \alpha_0 + \alpha_1 P_i + \alpha_2 WV_i + \alpha_3 M_i + \alpha_4 CD_i + \alpha_5 SS_i + \varepsilon_i \qquad (10)$$

We estimate this model alternatively using both linear and non-linear terms of mangrove width, different measures of storm surge, wind velocity, etc. The details are discussed in the results section.

3. Study area and measurement of variables

We study 803 villages from two adjoining districts called Jagatsinghpur and Kendrapada of the eastern Indian state of Orissa that were hit by a super cyclone with 256 km/h landfall wind velocity and 6 metres of storm surge in October 1999. In this area mangrove is the only wind barrier. The area is flat with average elevation below 10 metres everywhere (*District Planning Map for Cuttack, Jajpur, Kendrapada andJagatsinghpur of Orissa*, Reg. No. 112-NA/DP-1000–1000, National Atlas and Thematic Mapping Organisation, Calcutta, 2000) and mangroves are the only forests in these districts (District Statistical Abstract of Kendrapada, 2001). There were few patches of casuarina in some part of the coastline with average width in between 200 to 400 metres before the storm, but as per eye witness report these trees were no barriers to storm wind. They broke down with the first few strokes of cyclonic wind, whereas there was not much loss to mangroves even after many hours of storm fury. Mangroves very close to the storm landfall, probably just lost their foliage during the storm (Nayak et al., 2001) and thus, were able to provide continuous resistance to the storm throughout.

Villagers suffered multiple damages. People were poor either doing agriculture or fishing and houses were predominately *kutcha* structures when the cyclone struck. Only 2% of the rural houses had concrete structures (wall and roof) as per the 2001Housing Census of Orissa report. Analysis of human death for some of these villages caused mainly because of drowning due to storm surge showed that mangroves played a significant protective role in saving lives (Das and Vincent, 2009). For house damage analysis we selected only villages for which we could collect house damage data from government records. Measurement of variables is described below.

3.1 House damage data

Houses were damaged because of wind and storm surge and were put into three categories by the state government for the purpose of house damage compensation payment. The categories were swept away (SA), fully collapsed (FC), and partially collapsed (PC) houses; the PC houses being the residual category including very minor damage to houses[9]. We restrict our analysis to only two categories of house damage, (i) FC+SA and (ii) only FC houses as data on these categories were accurate and reflected actual wind damages to structures. We control for storm surge as some damage to FC houses could have been due to water and analyse both FC+ SA and only FC. SA houses were limited to near coast areas, within 10-12 km from the coastline and FC houses were witnessed near the coast as well as up to 50 km away from the coast. Of the 803 observations, 727 refer to aggregate number of damaged houses in a village whereas 76 observations are aggregates for gram panchayats (groups of villages).

3.2 Total number of families

House damage data reflect the number of families that received house damage compensation for their fully collapsed or swept away houses. However there is no estimation of total number of families present in a village. Both population and housing census of the state provides number of households in a village, but that proved to be a serious underestimation because of the joint family system in the study area. We use both total number of workers and total number of males above 6 years from the 1991 population census (they were more than 15 years by 1999 when cyclone struck)[10] as proxy for number of families present. We find that total workers reflect number of families quite accurately for villages in the cyclone eye. However number of adult males gives a better fit for villages falling under the outer eye area of the storm. Both econometric and simulation exercises support these results. The eye area

[9] As reported by government officers, number of partially collapsed houses was inflated as government wanted to help each family irrespective of the severity of damage to their house and thus had included many families with very minor damage to their houses in the partially damaged category.

[10] The cyclone struck in 1999 and we avoided interpolating the 1991 and 2001 census data to get the corresponding 1999 population figures because we feared endogeneity bias in 2001 population data. 2001 census was conducted after the cyclone,its impact could have affected population growth and migration.

covers villages in Jagatsinghpur district, while villages in Kendrapada district came under the outer eye area and probably these districts have different demographic pattern.

3.3 Wind velocity

Wind velocity over villages is measured using parameters from the Indian Meteorological department and cyclone track as described in National Institute of Disaster Management Report (Gupta and Sharma, 2000). The distance measures *d* are obtained using the GIS software. The storm made landfall in Ersama block of Jagatsinghpur district, moved approximately 30 km to northwest and then turned south away from the study area (see the cyclone path in figure 2). The landfall took nearly three hours and thus the maximum wind of the storm was reduced when it entered the interior track. In order to find out the position of the storm from where the villages received highest wind velocity, we calculated two measures of radial distances and wind velocities for each village, one from the landfall point and the other from the interior path of the storm. The first is called velocity_landfall and the other, velocity_interior. For 75% of the villages (605 of 803) velocity_landfall was higher than velocity_interior and for the rest, velocity_interior was higher. House damage being proportional to highest wind speed, we controlled for this aspect in two different ways: (i) retained the velocity_landfall measures for villages and used a dummy variable for the 298 villages that had velocity_interior to be higher, and (ii) defined wind velocity for each village as highest of the two. We tried both measures alternatively in econometric analysis and the first measure explained the damages much better.

3.4 Mangrove width and distance to coast

Mangroves are located in two major blocks to the north of the landfall point and all these areas fell under the cyclone outer eye. At the time of landfall, wind direction was vertical to mangroves, wind passed through the mangrove forest before it reached the villages and thus mangroves could have protected the villages. When the storm entered its interior path, the wind direction changed, was parallel to the mangrove forest and mangroves could not have provided any protection. As mangroves provided wind protection only at the time of the landfall, we measure mangrove width and coastal distance of villages following the wind direction at the landfall time. Such measures for interior position of the storm are not taken.

Tangential wind velocity being assumed to be the same along a circle, we draw *n* circles covering the study area taking landfall point as the centre. The circles show the path of the tangential wind. The distance from landfall to the farthest village of the study area is 82 km and we divide this distance into 75 circles taking care that mangroves of similar width remain in between two circles (see figure 2). Distance from coast and width of mangrove in this distance for villages lying on the circle or just adjacent is measured from the point where the circle crosses the coastline. These measures of coastal distance and mangrove width are labelled *dcoast_landfall* and *mangrove_landfall*. Measures corresponding to the minimum distance to coast (used for measuring storm surge) are labelled *dcoast_minimum*, and *mangrove_min_dcoast*. All measures are taken with the help of GIS.

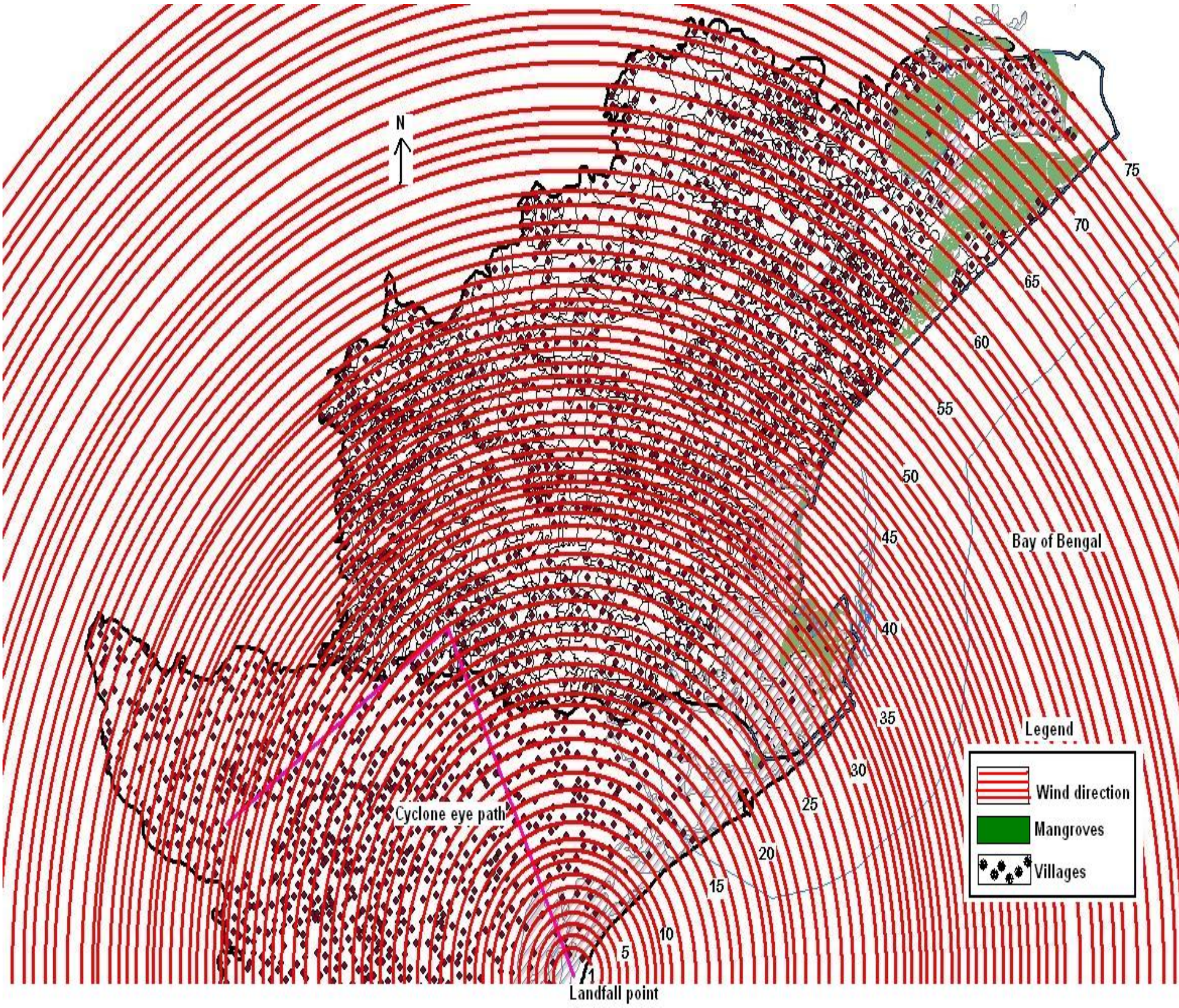

Figure 2: Study area, cyclone landfall, cyclone eye path, and wind direction over villages

3.5 Storm surge

Height of sea elevation at the coastline of study area is collected from a secondary source (Kalsi et al., 2004). Following equation (6) we took two measures of sea elevation for each village; one for the point from where wind entered the village, called *surge_landfall* as it corresponded to the direction of wind at the time of landfall and the other at the point located at a minimum distance to the village, called *surge_min_dcoast*. In econometric estimation, we used one of these measures at a time while in simulation exercise we combined these measures to get the highest storm surge effect on the villages.

4. Results: Econometric analysis

We estimate equation 10 here. Boxcox transformation favored a semi-log linear model. We tried alternative measures of wind velocity, number of families in a village, storm surge height at the coast, coastal distance etc in the equation to get the best fit. We estimated these regressions for three different sample areas, (i) the entire study area, (ii) only villages falling under eye and (iii) villages falling in outer eye area first using FC+SA and then only FC as dependant variable.

We expect mangroves' wind-damage protection capacity, if it exists, to be a non linear service of mangrove width as too thin a mangrove strand may not provide any protection and too wide a strand may bring in diminishing returns. We tested for this by adding square and cubic terms of mangrove variable and got the best fit for the use of cubic term. Adding the cubic term produced the highest R^2, minimum Root Mean Square Error, minimum AIC (not BIC) and most importantly a lower RMSE for out sample prediction after we divided the whole sample in a random ration of 74 to 26, estimated the model using 74% of the data and used the parameter estimates to calculate the RMSE for the rest 26% of the sample (Perez-Amaral et al., 2003).

On basis of higher R^2, lower RMSE and lowest AIC and BIC statistics, we use adult males as total number of families for the sample 1 and 3, but total number of workers as total number of families for sample 2 (villages falling under cyclone eye). Of the two ways of representing wind velocity, the use of the first one was preferred on the basis of these statistics. Sample 2 did not have mangroves, so we modify equation 10 as shown below and present the estimated coefficients for sample 1 and 3 in table 2.

$$Y_i = \alpha_0 + \alpha_1(adult\_males_i) + \alpha_2(velocity\_landfall_i) + \alpha_3(dummy\_high\_velocity\_interior_i) + \alpha_4(mangrove\_landfall_i) + \alpha_5(mangrove\_landfall_i)^2 + \alpha_6(mangrove\_landfall_i)^3 + \alpha_7(coastal\_distance\_landfall_i) + \alpha_8(surge\_landfall_i) + \varepsilon_i \quad (11)$$

Table 2 shows mangroves to be significant which is an indication that they have provided protection to houses from wind damages during the storm and this service is non-linear. However without information on tree canopy etc, this result is insufficient to prove wind protection service of mangroves.

Next, we explore whether the significance of mangroves was due to storm surge attenuation near the coast only or whether the variable is still significant for areas where storm surge could not cause house damage. So we repeat the estimation of this model by excluding each time some villages lying within a certain band width from the coastline as houses very near the coast are mostly affected by storm surge while in the interior, house damage should occur mainly because of wind. Table 3 presents these results only for mangrove variables.

Table 2: Ordinary Least Squares estimates with robust standard errors for regression coefficients of equation 11 for entire study area and for villages beyond cyclone eye

Variables	Dependant variable = log (FC+SA)		Dependant variable = log (FC)	
	Entire study area (n = 801)	Storm outer eye area (n =	Entire study area (n = 801)	Storm outer eye area (n = 627)

		627)		
Total adult males	0.0012*** (0.00007)	0.0013 *** (0.0001)	0.0011*** (0.00007)	0.0013*** (0.0001)
mangrove_landfall	-0.262** (0.109)	-0.229* (0.12)	-0.274** (0.112)	-0.281** (0.131)
(mangrove_landfall)^2	0.087** (0.034)	0.068* (0.038)	0.093*** (0.035)	0.091** (0.044)
(mangrove_landfall)^3	-0.007*** (0.003)	-0.005* (0.003)	-0.007*** (0.003)	-0.006** (0.003)
dcoast_landfall	-0.0035 (0.004)	0.005 (0.004)	0.002 (0.004)	0.0123 (0.005)
Velocity_landfall	0.00004 (0.0036)	0.026*** (0.008)	-0.0096 ** (0.004)	0.008 (0.015)
Dummy_high_velocity_interior	0.9337*** (0.1069	0.801*** (0.122)	0.874*** (0.111)	0.885*** (0.138)
surge_landfall	0.436 *** (0.100)	0.132 (0.154)	0.581*** (0.113)	0.389 (0.24)
Constant	2.66*** (0.348)	-0.476 (0.84)	3.61*** (0.45)	1.51 (1.72)
R^2	0.58	0.52	0.45	0.43
RMSE	0.856	0.862	0.994	0.948

Notes: Figures in parenthesis are robust standard errors; *, **, *** imply the level of significance as 10%, 5%, and 1% respectively.

Table 3: Ordinary Least Squares estimates with robust standard errors for regression coefficients of mangrove variables of equation 11 for samples beyond certain band width from coastline

sample (villages beyond 'x' km from coast)	Sample size	Coefficient estimates of		
		mangrove_landfall	(mangrove_landfall)^2	(mangrove_landfall)^3
Full sample	801	-0.262 (0.109)**	0.087 (0.034)**	-0.007 (0.003)***
beyond 5 km	772	-0.253 (0.111)**	0.085 (0.035)**	-0.007 (0.003)**
beyond 8 km	731	-0.299 (0.113)***	0.099 (0.035)***	-0.008 (0.003)***
beyond 10 km	699	-0.304 (0.113)***	0.099 (0.035)***	-0.008 (0.003)***
beyond 12 km	665	-0.314 (0.114)***	0.102 (0.036)***	-0.008 (0.003)***
beyond 15 km	604	-0.262 (0.12)**	0.083 (0.37)**	-0.006 (0.003)**
beyond 18 km	539	-0.318 (0.133)**	0.109 (0.049)**	-0.009 (0.005)*
beyond 20 km	493	-0.289 (0.133)**	0.102 (0.051)**	-0.009 (0.005)*

beyond 22 km	451	-0.331 (0.137)**	0.108 (0.05)**	-0.009 (0.005)*
beyond 28 km	341	-0.340 (0.16)**	0.103 (0.62)*	-0.01 (0.006)*
beyond 30 km	308	-0.339 (0.172)*	0.114 (0.069)*	-0.012 (0.007)*
beyond 32 km	282	-0.268 (0.176)	0.109 (0.07)	-0.01 (0.007)*
beyond 35 km	247	-0.152 (0.179)	0.095 (0.07)	-0.11 (0.007)

Notes: Figures in parenthesis are robust standard errors; *, **, *** imply the level of significance as 10%, 5%, and 1% respectively.

Table 3 shows that mangrove coefficients are significant for villages as far as 28 to 30 km away from coast and insignificant beyond that distance. This gives strong evidence that mangroves provide some wind protection because storm surge was limited to villages within15 km from coast and beyond that the cause of damage was strong wind.

To further test the hypothesis whether mangroves provided wind protection or not, we simulate house damages using equation (7) with different parameter values and compare with actual house damages witnessed in villages.

5. Results: Simulation exercise

We measure the combined impact of wind velocity and storm surge using equation (7) with different parameter values. Villages are grouped according to the combined impact. The actual house damages is compared to the expected damages as described in table 1.The parameters and their values are explained in table 4.

Table4: Parameters used and approximate values

Parameter	Definition	Approximate Value
β	Proportionality between the house damage and the square of wind velocity.	Depend on house quality and probably varies from area to area. For the study area that has maximum houses as *kutcha* structures, we take $\beta = 6.2/(62^2) = 0.001613$ (see equation 9)
r	Radius of the cyclone eye	15 km (IMD, 2000)
μ	Rate of decline of potential radial wind with distance away from the cyclone eye	-0.6 (Roy Abraham et al.,1994)
ν	Exponential rate of decline of maximum wind per hour	-0.0991 (Singh and Bandyopadhyay, 2003)
t	Number of hours after landfall when the storm eye reached the village	3 (Gupta and Sharma, 2000)
V_{Max}	Wind speed at the cyclone eye wall region	(i) 256 km/h at landfall (IMD, 2000)

		(ii) 190.16 km/h ($=256*e^{-0.0991*3}$) on the straight line eye track as shown in Fig 2 as the landfall is reported to have taken 3 hours.
S_{Max}	Height of maximum sea elevation	6 metres (Kalsi et. al., 2004)
α	Exponential rate of decline of storm surge height per km of coastal distance as it moves inland after hitting the coast	-0.14607 per km of coastline without mangroves for the study area[11]
η	Exponential rate of decline of storm surge per km of mangrove forest it travels.	We expect it to be some multiple of α and have tried α, 2α, 3α, etc. and finally retained η = 2α = -0.29214.[12]
λ	Exponential rate of decline of radial wind speed per km of coastal distance (east to west)	To be determined (?)
δ	Exponential rate of decline of radial wind per km of mangrove forest it travels	To be determined (?)

Of the 11 parameters, values of 7 are taken from secondary sources, values of two related to storm surge (α, η) are measured using information from the study area as described in footnotes and values of the rest two related to wind velocity (λ, δ) is assumed to be zero. We approximate their values as we find difference between the actual and expected damages later. We do this analysis separately for eye and outer eye area. Even though house type is very similar over the study area as per the housing survey, there may be some differences at the village level and we did not have complete information on house quality and other specific features of each village. So we compare average of actual house damages with the expected damages for groups of villages either facing same range of wind velocity or lying within the same band width from coast etc so that village specific features cancel out.

[11] The landfall area of the storm had no mangrove, the sea elevation was 7 meters and the storm surge is reported to have entered 29 -30 km inland. This means the rate of reduction of wave height was approximately -0.14607 per km if we expect an exponential rate of decline. The rate of decline will be -0.2925 (or -0.45 if surge height decrease linearly) if data from other areas (Pielke et al., 2003) is used.

[12] Based on field experiments in *Vietnam*, the rate of wave attenuation by mangroves or the rate of decrease in wave heights after crossing the forest varied from 0.52 to 0.78 to 6.7(Source: PPT presentation, Dr. Ngo Ngoc Cat, 2006) for different areas. However, these values did not explain the swept away houses witnessed in the study area. We measured surge height over villages using values of η = 0, α, 2α, 3α, 4α etc and measured the correlation coefficient between surge height and swept away houses for near coast areas (d_landfall<50 &dcoast_landfall<20) where houses got washed away mainly because of surge, not because of flooding from rivers. This was done for outer eye area where mangroves are located. Correlation coefficient was highest and significant for the value of surge height based on η = 2α = -0.29214. This means the reduction in height of storm surge after passing through a km of mangrove forest is two times higher than the reduction in height if the surge travels one km distance without mangroves.

5.1 Simulation for eye area

All villages falling under the cyclone eye face the same wind velocity, the maximum wind called V_{Max} and the decline in maximum wind is mainly considered with respect to time (the cyclone is a slow moving system), not coastal distance. The entire eye area faces the maximum storm surge, the S_{Max}. So we take the following measures for wind velocity (12) and storm surge (13) respectively to be used in equation (7). Parameter ν is the exponential rate of decline of maximum wind and t is the number of hours after landfall when the storm reached the village.

$$V = V_{Max} e^{-\nu t} \qquad (12)$$

$$W(S_{Max}, a, m_2) = S_{Max} e^{-(\alpha a + \eta m_2)} \qquad \mathbf{(13)}$$

The parameter values used to calculate expected damages for the eye area are the following:

$V_{Max}=256$, $S_{Max}=6$, $\alpha = -0.1407$; $\eta = -0.29214$; $\nu = -0.0991$; $t = 3$ hrs (Source: table 4)

The storm eye path is described and shown in Fig 2. 174 villages of the study sample are located within a 15 km radius of this line and thus in the eye area. The maximum wind was 256kmh^{-1} during landfall and was likely to reduce to 190kmh^{-1} as landfall took nearly 3 hours and ν = -0.0991 per hour. During landfall, villages within 15 km radius of landfall point received wind velocity of 256kmh^{-1} and the rest of the 174 villages were getting tangential wind. Damage to houses being proportional to the highest wind speed, we compare the radial wind velocity of these villages with 190 and retain the higher one. Of the 174 villages, the wind speed was 256kmh^{-1} for 34 villages, 190kmh^{-1} for 97 villages and in between 255kmh^{-1} to 199kmh^{-1} for the rest 43 villages. The maximum storm surge was 6 meters at the coast and the storm surge height over the villages is measured between 0.0033 to 5.04 meters, the highest (0.35 to 5.04) for villages near landfall. Very little surge cannot cause house damage. The minimum surge height over villages with swept away houses was found 0.4 meters. Thus, we added the square root of the equivalent wind speed to wind velocity of those villages that had storm surge height equal to or above 0.4 meters to calculate combined stress on houses. With only 174 villages, we put them in 3 categories to compare expected and actual damages.

We categorise the villages by two criteria, (i) wind velocity (ignore the storm surge) and (ii) combined stress (total impact of wind velocity and storm surge). There were no mangroves on the eye path of the storm.[13]

[13] Some mangroves of outer eye area were in path of the storm surge for some of the villages, but these villages being far off from coast surge height was less than 0.1metre and thus mangroves could have provided no protection.

Table 5 and table 6 show these comparisons for the sum of FC and SA houses and only for the FC houses. It seems that combining wind and storm surge better explains the storm impact on the villages and the damages. Actual damages match expected damages better in table 6.

Comparisons in table 5 and 6 put confidence on our approach and we repeat this procedure for cyclone outer eye area where mangroves are located.

Table 5: Wind velocity, expected and actual damages witnessed over villages

Wind velocity over the villages	Expected damage	Number of villages	Actual damage witnessed (= (FC+SA)/total_workers_1991)	Actual damage witnessed (= (FC)/total_workers_1991)
Greater than 248 kmh^{-1}	Nearly 100%	44	101%	78.8%
248 > WV > 217	76 – 90%	23	87.6%	83.9%
217 > WV ≥ 190	56 – 75%	107	78.7%	78.2%

Table 6: Combined_stress (combined effect of storm surge and wind), expected damage and actual damage witnessed over villages

Combined stress over the villages (kmh^{-1})	Expected damage	Number of villages	Actual damage witnessed (= (FC+SA)/workers_1991	Actual damage witnessed (= (FC)/workers_1991
Greater than 248	Nearly 100%	54	100%	81.8%
248 > Combined_stress > 217	76 – 90%	15	84.7%	80.7%
217 > Combined_stress ≥ 190	56 – 75%	105	78%	77.9%

5.2 Simulation for outer eye area

Of the 627 villages located in the outer eye area, 419 received higher wind velocity during the storm landfall when the wind direction was vertical to the mangrove forest as shown in Fig. 2. As wind reached these villages after passing through the forest, we expect the mangroves to have protected these villages during this time. 208 villages that received highest wind velocity during the interior movement of the storm are not expected to show any wind protection from mangroves as the wind direction was parallel to mangroves during this period. So we delete these 208 villages from the simulation exercise. In this area, total male population above 6 years of age in 1991 census is used as proxy for total number of families in the comparison. Unlike in the eye areas, villages with as low as 0.3 metre high storm surge had houses swept away. So we measure combined stress by adding equivalent wind to the wind velocity for all those villages that had storm surge height either equal or more than 0.3 metres. Equation 7 is used to measure the expected damages for villages.

First, we assume λ = δ =0 (mangroves give no wind protection) and compare the expected and actual damages between mangrove and non mangrove areas. If mangroves give no protection, then mangrove and non-mangrove areas with similar combined stress level (wind and surge) should have same level of damages and actual damage should match the expected damage. In case mangrove areas are found to have lower damage than expected, then λ and δ are non zero and the values of these two parameters can be calibrated so that expected damage match the actual. The combined impact of wind velocity and storm surge on villages varied from 96kmh^{-1} to 250kmh^{-1}, but only 6 villages had more than 201kmh^{-1} combined stress and they had no mangroves. So we start the upper limit at 201kmh^{-1}, not above.

Table 7 presents the comparison of expected and actual damages and actual damages seem to match expected damages for the entire area for combined stress levels more than 155kmh^{-1}, but less than expected for stress levels less than 140 km/h (column 3 and 4). However, in almost all range of combined stress except one, villages with mangroves suffered less damage compared to villages without mangroves. These reductions are larger (around 20%) for villages facing stronger impact from storm than for villages facing lower impact (around 4%).

Table 7: Combined_ stress (combined effect of wind velocity and storm surge) measured from landfall, expected and actual damage for villages with mangrove and without mangrove

Combined stress (CS) over villages (kmh^{-1})	Expected damage	Actual damage witnessed (whole sample)		Actual damage per village with **no mangrove**			Actual damage per village **with mangrove**		
		FC+SA /adult_ males	FC/adult _males	Number of villages	FC+SA/ adult_males	FC/ adult_ males	Number of villages	FC+SA/adult_males	FC/ adult_ males
Greater than 201	More than 65%	90.7	90	6	90.7	90	0	0	0
201> CS >186	56 - 65%	65.1	62.8	7	71.6	70.6	5	55.9	51.8
186 > CS > 176	49 – 55%	55.5	55	6	65.4	64.8	6	45.6	45.2
176 > CS > 155	39 – 48%	46.4	46.4	6	51.0	51.0	51	45.9	45.9
155 > CS > 140	31 – 38%	41.2	40.1	14	44.7	42.2	56	40.3	39.6
140 > CS > 124	25 – 30%	19.0	19.0	62	18.4	18.4	27	20.2	20.2
124 > CS > 112	19 – 24%	10.9	10.8	76	12.1	12	29	7.7	7.7
112 > CS > 93	14 – 18%	6.2	6.1	0	0	0	62	6.2	6.1

Villages facing combined stress between 124 and 140kmh^{-1} suffered a marginal 2% higher damage when they had mangrove compared to villages without mangroves. These turn out to be villages with fragmented and small patches of mangroves in their coastline (table8), which may explain the higher damage.

Unlike in the cyclone eye, the difference between the two measures of house damage (FC+SA and FC) is marginal for these villages, so the main cause of house damage is wind velocity and the fact that mangrove areas witnessed less damage is evidence of wind protection service of mangroves. However, the damages shown above are averages for all villages lying within a certain range of cyclone stress and are picked up from different locations. To examine the wind protection service more systematically, we group the villages on the basis of their location (villages lying within a certain range of distance from landfall point and from the coastline) and then compare the damages with distance away from coast. Table 8 shows this comparison.

We use distance *d* to categorise the villages and this distance being the main variable that help measure wind velocity of a village, we indicate the corresponding expected damage for each category. We follow the same categories as shown in table 7.These are shown in first two columns of table 8. Next we group villages on the basis of their coastal distance taking a band width of 10 km each time (10 to 20 km, 20 to 30km etc). For each category, we further characterise the villages with mangrove and without mangrove and then note down the average damage percentage (FC+SA/adult males and FC/adult males) for each sub category. These are shown in the last 4 columns of table 8. The average width of mangroves is shown in 3rd column.

Table 8: House damage of villages lying within different band width from landfall point of cyclone and coastline

Radial distance from the landfall (in km	Expected house damage	Average mangrove width (km)	Actual house damage (FC+SA/adult males, FC/adult males)			
			Villages within less than 10 km from coast	Villages within 10 to 20 km from coast	Villages within 20 to 30 km from coast	Villages within 30 to 40 km from coast
15.1 - 25.5	More than 56	0	110, 110	97.4, 95.5	81, 81	No village
25.5 – 28	49-56	0	66, 65	52, 51.5	No village	No village
28 - 34.5	39-48	0	89, 88.1	42, 41.6	55.5, 55.6	No village
		1.36	76, 71	47, 46.8	37.7, 37.7	31, 31
34.5 - 41	31-38	0	No village	No village	No village	No village
		2.61	48.7, 48.7	42.2, 41.6	39, 39	No village
41 - 50	25-30	0	35.7, 33.9	21, 21	16.8, 16.8	No village
		0.46	41, 38.5	30, 30	21, 21	No village
50 - 59	19-24	0	18.3, 17.9	13, 13	9, 9	13, 13
		0 .44	7.7, 7.3	7.5, 7.4	12.7, 12.7	15.3, 15.3
59 - 82	14-18	0	20, 18.6	No village	No village	No village
		1.86	9.5, 8.7	7.2, 7.1	5.6, 5.6	7.7, 7.7

Comparison of damages for different bandwidth from coast clearly shows that the radial tangential wind declines with distance from coast. Villages within 20 to 30km from coast witnessed lower damage compared to villages within 10 to 20km and these villages have lower damages compared to villages within zero to 10 km from coast. Thus neither the parameter λ is zero nor the assumption that radial wind velocity is identical along every circle at *d* km away from the eye. This validates our first hypothesis that radial wind declines with coastal distance.

Table 8 also validates the existence of wind protection services of mangroves. Mangroves exist beyond 28 km distance from landfall and we have villages with and without mangroves in four categories i.e. within 28 -34.5km, 41- 50km, 50 – 59km and 59- 82km band width from landfall. Comparing the damage for villages within 10 km from coast for these categories, we find mangrove villages to have witnessed less damage everywhere compared to non-mangrove villages except one category i.e. 41 – 50km band where they suffered 5% more damage. Mangroves within 41 – 50km distance from landfall are small and fragmented patches, whereas in other bands they are a part of a continuous patch of forest. This means mangroves provide storm protection when they exist in continuous and large patches; otherwise they aggravate the storm damage occurrences.

The reduction in damage for mangrove protected villages is 13% for villages of 28 – 34.5 km band (17% in case of only FC), 10.6% for villages of 50 – 59 km band and 9.5% for villages of 59 – 82 km band. These differences are much higher if we consider the differences between the average percentages of only FC houses. This means (i) wind protection of mangroves is higher for villages close to landfall or within high impact zone of storm and lower for villages in low impact zone and (ii) mangrove protection is much higher for wind caused damages (FC houses) than for wind and surge caused damages (FC+SA houses).

Next we calibrate the approximate value of parameters λ and δ making use of these reduced damages. We (i) measure the actual combined stress on villages corresponding to the actual damages witnessed using inverse of equation (9) , (ii) subtract the impact of storm surge on villages following the same rule as we followed to add it to wind velocity (if surge height $\geq$ 0.3), (iii) call the difference '*actual wind velocity'* and calculate its average for the groups of villages as shown in table 8, and (iv) measure the exponential rate of decline of radial wind (λ) per km of coastal distance for each band width of radial distance.[14] We measured λ separately for villages with and without mangrove and find it to vary between -0.007 to -0.036 for the former and between -0.0035 to -0.0168 for the later. The average rate of decline per km of coastal distance comes is -0.013 for non-mangrove areas and -0.011 for mangrove areas. Mangroves reduce the wind velocity at the coast to a great extent and mangrove protected villages start then with a lower wind velocity, which could explain the lower rate for mangrove areas.

[14] For example, for the band width 15.1 – 25.5, λ = ln (actual wind corresponding to 81% house damage / actual wind corresponding to 110%house damage)/20

We measure the value of δ, the exponential rate of decline of wind velocity by km of mangroves by comparing the actual wind velocities of villages within 10 km bandwidth from coast using the average width of mangroves in each category with reduced damages i.e. between 28 – 34.5, 50 – 59 and 59 - 82 radial distances. Even within 10km distance from coast, the villages behind mangroves would be further off from coast than the ones without mangroves and are likely to get reduced cyclone impact. So we control for coastal distance while calculating the value of δ using equation (14), where *AWV_M* is actual wind velocity corresponding to the damage for villages in 10 km from coast with mangrove, *AWV_NM* is actual wind velocity corresponding to the damage for villages in 10km from coast without mangrove, λ_1 is the rate of decline of radial wind in non-mangrove area (-0.013), λ_2 is rate of decline of radial wind in mangrove area (-0.011), $dcoast_1$ is average coastal distance of villages within 10 of coast without mangrove, $dcoast_2$ is average coastal distance of villages within 10 km of coast with mangroves, and *width_mangrove* is average width of mangroves for these villages.

$$\delta = \frac{\ln\left(\left(\frac{AWV\_M}{AWV\_NM}\right) \Big/ e^{-\lambda_2 dcoast_2 + \lambda_1 dcoast_1}\right)}{width\_mangrove} \qquad (14)$$

The δ value per km of mangrove width varied from -0.05738 to -0.7201 and a weighted average using average width of mangrove as weights resulted in $\delta = -0.16388$. Using $\lambda = -0.0122$ (average of -0.013 and -0.011) and $\delta = -0.16388$, we calculated house damages for villages. The results match well for house damages beyond 59km of radial distance where the study areas have lots of mangroves, but underestimates highly the damages for areas closer to eye or with less or no mangroves, which means the value of λ for these areas is much lower than -0.0122.

6. Conclusion

We examined wind protection services provided by mangrove forest during a super cyclone using data on number of damaged houses in a village. Both storm surge and high wind caused house damage and we controlled for these impacts at villages level. We used an econometric approach complemented by model simulation using empirical data and obtained results that supported our hypothesis that mangroves provide protection from wind damages of a storm especially in areas where mangroves are continuously spread in large patches. We assumed tangential wind velocity to be decreasing exponentially with coastal distance and mangrove width in that distance and estimated the rates of decrease to be around -0.0122 and -0.16388 respectively. These values explain well the damages in areas with widespread mangroves, but underestimate the damages for other areas, especially ones close to storm landfall, where we estimate these values to be much lower. These measures can be improved with better quality data on exact nature of house damage and house quality before the storm. However our study shows substantial evidence that mangroves provide more storm protection than previously established and to people who are much far away from forest than the general belief. Thus it is essential that planners account for mangroves potentials to help mitigate storm disasters in addition to all other benefits that mangroves produce when they envisage mangrove conservation or planting new mangrove.

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9. Appendix

Appendix table 1: Wind velocity and Storm Surge height of tropical storms

Wind velocity(km/h)	Storm surge height (meter)
64-87	0
88-118	1
119-153	1.2-1.5
154-177	1.6-2.4
178-209	2.5-3.6
210-250	3.7-5.4
More than 250	6

Source: http://en.wikipedia.org/wiki/Saffir-Simpson_Hurricane_Scale

Appendix table 2: Average wind speed and types of damage to different structures

Source: IMD (http://www.imd.gov.in/section/nhac/dynamic/faq/FAQP.htm#q39)

Range of different wind speed (km/h)	Expected damage to structures
Less than 62	No damage
62-87	Damage to thatched huts. Overall: **Minor to Moderate**
88-117	Major damage to thatched huts/houses, roof tops blow off, metal sheets may fly off. Overall: **Moderate**
118-167	Total destruction of thatched house, extensive damage to all types of kutcha houses, some damage to pucca house. Overall: **Large**
168-221	Extensive damage to all types of kutcha houses, some damage to pucca house. Overall: **Extensive**
More than 222 (or 222 – 300)	Extensive damage to non-concrete residential and industrial buildings, structural damage to concrete structures. Overall: **Catastrophic**