Global Environmental Change 70 (2021) 102328

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

The global value of coastal wetlands for storm protection

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ARTICLE INFO

Keywords:
Coastal wetlands
Storm protection
Economic valuation
Bayesian analysis
Avoided damages
Avoided deaths

ABSTRACT

Coastal wetlands provide a range of valuable ecosystem services, including protecting coastal communities from storms. We estimated for the first time the global value of these storm protection services for all coastal wetlands for both damages avoided and lives saved. We used the historical tracks of 1,014 tropical cyclones since 1902 that recorded property damage and/or human casualties in 71 countries/regions. We used Bayesian and OLS statistical techniques to relate storm damages and lives lost to: wind speed, storm forward speed, the year of the storm, the volume of ocean water proximal to landfall, and GDP, population, and coastal wetlands in the swath of the storm. Based on current storm probabilities, we estimate the median annual global value of coastal wetlands for storm protection at $447 billion/yr (2015$US) ($213 - $837 billion/yr, 90% CI) and 4,620 lives saved per year (3,320 – 6,550, 90% CI). The 40 million hectares of coastal wetlands in storm prone areas provided an average of $11,000/ha/yr in avoided storm damages. The frequency and intensity of tropical cyclones has been increasing in recent decades and is projected to further increase with climate change. Consequently, the already significant benefits from protecting and restoring coastal wetlands will become increasingly important and valuable in the future. These results justify much larger investments in conservation and restoration of coastal wetlands.

1. Introduction

Coastal wetlands provide a large assortment of ecosystem services (Costanza et al., 2014; de Groot et al., 2012; Finlayson et al., 2015). One particularly vital service is the protection of both lives and property from the impacts of tropical cyclones (Rahman et al., 2018). Coastal wetlands reduce the damaging effects of tropical cyclones on coastal communities by absorbing storm energy in ways that neither solid land nor open water can (Simpson and Riehl, 1981). The mechanisms involved include decreasing the area of open water (fetch) for wind to form waves, increasing drag on water motion and hence the amplitude of a storm surge, reducing direct wind effect on the water surface, and directly absorbing wave energy (Boesch et al., 2006; Costanza et al., 2006). Wetland vegetation contributes in two ways: (1) by decreasing surges and waves; and (2) by maintaining shallow water depths that have the same effect. Wetlands also reduce flood damages by absorbing flood waters caused by rain and moderating their effects on built-up areas.

Relatively few previous studies have addressed the ecosystem service value of storm protection provided by coastal wetlands. Some have focused on a particular type of wetland, (e.g. mangrove forests), on specific storms, or for specific regions (Badola and Hussain, 2005;

https://doi.org/10.1016/j.gloenvcha.2021.102328
Received 1 April 2021; Received in revised form 7 July 2021; Accepted 14 July 2021

Barbier, 2007; Barbier and Enchelmeyer, 2014; Barbier et al., 2013; Boutwell and Westra, 2016; Danielsen et al., 2005; Das and Vincent, 2009; Farber, 1987). A few have addressed the national scale using statistical analysis of historical storms for the US (Costanza et al., 2008; Sun and Carson, 2020), Mexico (Pérez-Maqueo et al., 2018), China (Liu et al., 2019; Ouyang et al., 2018), and Australia (Mulder et al., 2020).

Costanza et al. (2008) analysed the storm damages from 34 major hurricanes avoided by coastal wetlands in the United States. They estimated an average value of more than $US 8000/ha/yr and a total value for the US Atlantic and Gulf coast wetlands of more than $US 23 billion/yr (in 2007US$). Value in this case is estimated as the dollar value of the damages avoided by having the coastal wetlands in place. Using methods similar to Costanza et al., Ouyang et al. (2018) estimated the value of coastal wetlands in Australia and China at $US 53 and 199 billion/yr.

More recently, Sun and Carson (2020), using a different functional form and improved data, analysed property damage caused by 88 tropical storms hitting the US from 1996 to 2016. They estimated an average value of $1.8 million/km^2/yr ($18,000/ha/yr).

These studies used statistical analysis of the relationships between storm damages, wetlands, and storm characteristics. A different approach uses process based hydrological modelling of storm impacts on flooding and flood damages. Recent examples at the global scale estimate the flood protection value provided by coral reefs (Beck et al., 2018) and mangroves (Menéndez et al., 2020). This approach reinforces and provides some of the causal mechanisms behind the statistical relationships we find.

Here we extend and update the statistical analyses to the global scale using data on 1014 tropical cyclones beginning in 1902 that have hit 71 countries/regions and caused either damages or human deaths. This is the first global statistical analysis of the value of all coastal wetlands for avoiding property damage, and the first estimate of the lives saved by coastal wetlands.

We have taken advantage of the confluence of improved storm tracking, global land use mapping, and global damage assessment databases, along with improved computational capabilities to model the relationships between coastal wetlands and avoided damages and deaths from tropical cyclones.

To determine the storm protection value of coastal wetlands, we developed models that predict the property damage and lives lost caused by tropical cyclones. Tropical cyclones are grouped into categories. Tropical storms are cyclones with wind speeds between 34 and 63 knots (sometimes called category 0). Storms with wind speeds>64 knots are classified as hurricanes (or typhons) ranging in category on the Saffir–Simpson hurricane wind scale from 1 to 5, with wind speeds ranging from 64 to 82, 83–95, 96–112, 113–136, and > 137 knots respectively. Property damage and lives lost are based on the spatial and physical characteristics of the storms themselves and the social, economic, and environmental characteristics of the land and water in the swath of the storm.

To do this, we needed to assemble data on three basic elements: (1) storm tracks and characteristics; (2) wetland area, GDP (as a proxy for infrastructure), and population in each storm's swath; and (3) storm damages and human lives lost in each storm's swath. We describe details of how we assembled this data and how we used it to model the relationships between these variables in Supplementary Materials and Methods. In addition, an interactive story map that describes the data and methods is available at: (https://storymaps.arcgis.com/stories/4be8afd6872145f585782f6e3f8fbe95)

Here we describe our general approach.

2. Approach

In general, we used methods similar to those used in Costanza et al. (2008) supplemented with Bayesian estimation techniques that enabled effective use of a wider range of data. The US was the focus for the Costanza et al. study because sufficient data was not available for other countries/regions to carry out the analysis. In the intervening years, similar studies showing the role of wetlands in reducing storm damages have been carried out in Mexico (Pérez-Maqueo et al., 2018), China (Liu et al., 2019; Ouyang et al., 2018), and Australia (Mulder et al., 2020).

In summary, in this analysis we:

1. Incorporate global data on tropical cyclone tracks back to 1902. Storm track data is from the NCDC International Best Track Archive for Climate Stewardship project (IBTrACS v3 - https://data.nodc.noaa.gov/cgi-bin/iso?id = gov.noaa.ncdc:C00834), which has storm track data for all years from 1900 to the present. For example, Fig. 2 is a map of the global storm tracks for the year 2003. Fig. 3 shows all tropical cyclones by category from 1900 to 2020. In total, there have been 5913 tropical cyclones (categories 0–5) over this period. Of these, we used only those which had recorded data on either damages or deaths (see point 4 below) – a total of 1014.
2. Incorporate new global land use data from the Global Human Settlement Layer (GHSL -https://ghsl.jrc.ec.europa.eu/datasets.php) to estimate population and built up area in the paths of hurricanes. We derived the area of coastal wetlands (including mangroves, salt marshes, and swamp forests) in the swath of each storm from a time series map of landcover produced by the European Space Agency.
3. Incorporate newly available time series of night-time satellite imagery combined with time series of national GDP to estimate GDP in the swath at the time of each storm. We use GDP as a proxy for the amount of infrastructure in the storm swath that can be damaged.
4. Incorporate data from the International Disaster Database (EM-DAT - https://www.emdat.be/) to provide total property and other economic damages, number of individuals affected, and deaths for each storm. We limited the storms used in our analysis to tropical cyclones that made landfall and caused either damages or deaths.
5. Incorporate a Bayesian statistical approach, which has been shown to be more appropriate for our analysis, given the complex nature of the data from multiple sources over long time spans (Mulder et al., 2020).

By combining data from these sources, we created a database of 1014 storms, with a total of 1288 landfalls (compared with 34 in Costanza et al. (2008), and similar numbers for the other previous studies – see Table 2). A spreadsheet showing the full list of data used in the analysis is given in Supplementary Information (Table S1).

Using the Bayesian analysis described in Supplementary Materials and Methods, we use a log–log model specification to estimate *damages/GDP* as function of wind speed of the storm (*windspeed*), forward speed of the storm (*speed*), wetland area in the swath of the storm (*wetlands*), and volume of water in the ocean proximal to the storm landfall (*volume*). We also included the year of the storm minus 1900 (*time)* as a (non-transformed) linear variable. *Time* was not log transformed due to irregularities in the model residuals.

We modelled the total damage caused by storms in 2015$US (*damages*) as a random variable where $\ln\left(\frac{damages}{GDP}\right)$ is normally distributed with standard deviation σ and mean μ given by:

$$\mu = \alpha + \beta_1 \bullet \ln(wetlands + 1) + \beta_2 \bullet \ln(\text{windspeed}) + \beta_3 \bullet \ln(\text{speed}) + \beta_4 \bullet \ln(\text{volume}) + \beta_5(\text{time}) \quad (1)$$

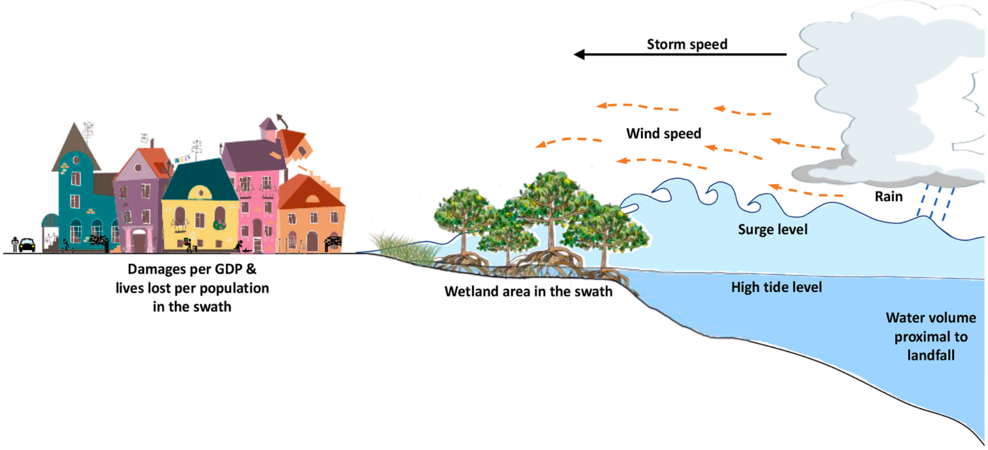

Fig. 1. Diagram of the effects of tropical storms on damages/GDP and lives lost/population in the swath of a tropical cyclone, as moderated by coastal wetlands.

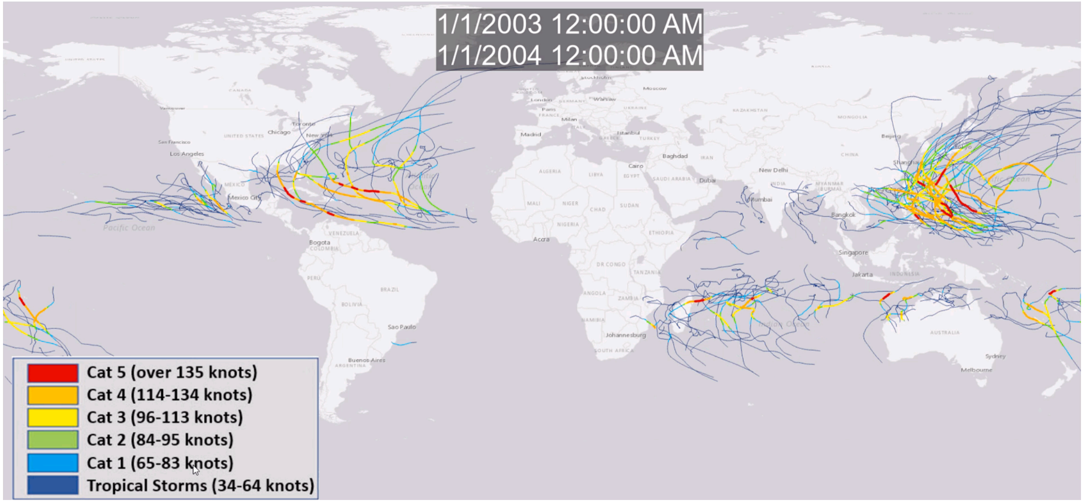

Fig. 2. Global tropical cyclone tracks in 2003 by category. See https://www.dropbox.com/s/1a7b5ysuldoytil/Cyclones_1900_2_2020.mp4?dl=0 for maps of tracks in all years from 1900 to 2020.

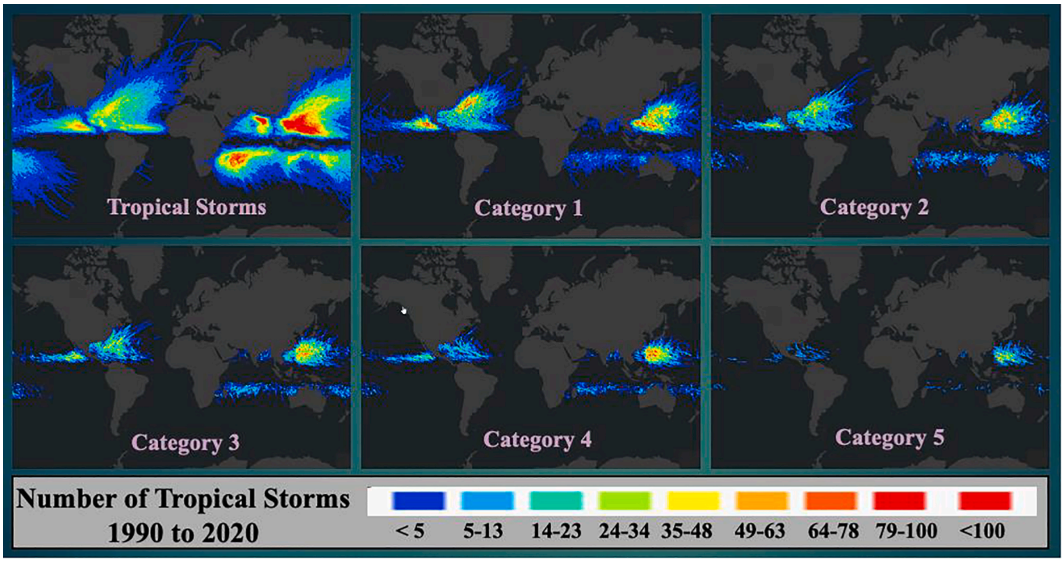

Fig. 3. Tracks of all tropical cyclones by category from 1900 to 2020.

For the damages model, we did not use storms occurring prior to 1944 as damage data during the 1902 – 1944 period were found to be unreliable due to some values falling well outside the expected range. The coverage of storms for this period was also quite incomplete. We assumed that the post-WWII period was the beginning of more reliable tropical cyclone tracking and more reliable damage assessment. This restriction eliminated only 11 storms, which barely affected the size of our sample. Removing these 11 storms left 972 storms making landfall. Of these, 673 caused damages that were recorded in EM-DAT. These 673 storms were included in the damages model.

3. Results

The marginal posterior parameter estimates derived from the Bayesian analysis using Equation (1) applied to the damages database are shown in Fig. 4. Summary statistics are given in Table 1.

These parameter estimates indicate that coastal wetlands have very significant effects on reducing damages from tropical storms: $\beta_1 =$ -0.236. This estimate of this parameter is consistent with estimates in previous studies and estimates using a subset of this dataset and standard OLS methods (see Supplementary Materials and Methods). Table 2 shows the range of these estimates. The resulting values of coastal wetlands for storm protection are also consistent with these previous studies, as we show further on. Here we expand the analysis to a longer term, global perspective, use Bayesian analysis techniques to better handle data uncertainty while estimating the value of coastal wetland for both preventing property damages and saving lives.

The Bayesian R^2 for our damages model is 0.49. Fig. 5 is a plot of predicted damages vs. observed damages for the 673 storms included in the analysis where predicted damages represent the median value for damages based on the joint posterior distribution (which includes estimates for the GDP at the time of the storm).

Table 1
Median parameter estimates and 95% highest posterior density credibility intervals for the model in Eq. (1).

$$\ln\left(\frac{damages}{GDP}\right) = -7.992 - 0.236\ln(wetlands + 1) + 3.298\ln(windspeed) - 0.55\ln(speed) + 0.137\ln(volume) - 0.058(time)$$

	α	*wetlands*	*windspeed*	*speed*	*volume*	*time*
2.5%	−12.314	−0.350	2.712	−1.145	0.007	−0.082
Median	**−7.992**	**−0.236**	**3.298**	**−0.550**	**0.137**	**−0.058**
97.5%	−3.836	−0.120	3.893	0.044	0.270	−0.035
p-values	< 0.001	< 0.001	< 0.001	0.037	0.021	< 0.001

Windspeed is the most obvious contributor to damages and has a significant positive effect ($\beta_2 = 3.298$). This value is consistent with the well-known relationship that the power in wind increases as the cube of windspeed. Storm forward speed has a significant negative effect on damages ($\beta_4 =$ -0.55) since slower moving storms have more time to cause damages from rainfall. The volume of water in the ocean proximal to landfall has a significant positive effect on damages ($\beta_5 = 0.137$) since more water in the coastal ocean proximal to landfall provides more water for storm surges and more thermal energy to support the storm.

Finally, we show that time (year −1900) has a significant negative effect on damages ($\beta_3 =$ -0.058). This is because technology is improving for tracking and monitoring storms and assessing damages, and building codes are improving the ability of built infrastructure to resist damages. As far as we are aware, this identification of a time trend that captures a

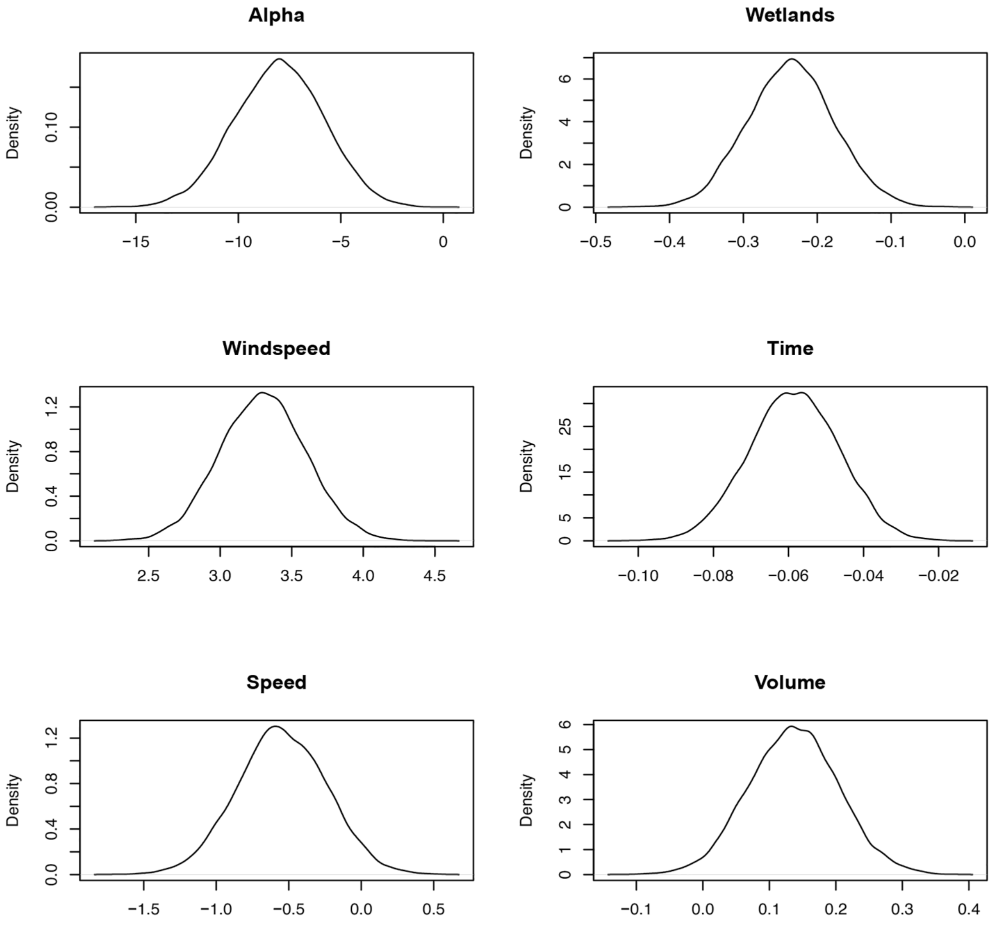

Fig. 4. Marginal posterior distributions of parameter estimates for model given by Equation (1).

Table 2
Range of estimates of β_1 (wetlands coefficient) from some previous studies for storm damages and this study using both OLS multiple regression methods and Bayesian methods.

Source	Location	# of storms	Time period	β_1 Coefficient	Adj R^2	Statistical analysis method
(Costanza et al., 2008)	USA	34	1980 to 2005	−0.770 ***	0.60	Regression
(Liu et al., 2019)	China	127	1989 to 2016	−0.197 **	0.59	Regression
(Sun and Carson, 2020)	USA	88	1996 to 2016	−0.576 ***	0.52	Regression
(Mulder et al., 2020)[a]	Australia	44	1967 to 2016	−0.651 ***	0.31[d]	Bayesian analysis
(Mulder et al., 2020)[a]	Australia	44	1967 to 2016	−0.304 **	0.16	Regression
This article	Global	673[b]	1944 to 2019	−0.236***	0.49[d]	Bayesian analysis
This article	Global	509[c]	1902 to 2019	−0.267 ***	0.21	Regression

Significance levels: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

[a] Mulder et al., (Mulder et al., 2020) reported results from both Bayesian analysis and from multiple regression, hence both results presented here.

[b] Including all storms that recorded property damage.

[c] Including only single landfall storms within a country/region since independent observations of damages suitable for standard regression were unavailable to separate the damages by landfall for storms making multiple (>1) landfalls within a country/region.

[d] Bayesian R^2 are estimated differently from OLS R^2. See equation 3 in Data and Methods.

reduction in damages relative to GDP is novel.

We had initially included the area of coral reefs in the storm swath as an additional explanatory variable, but found that it was not statistically significant. This is most likely due to the complexity of the interactions between coral reefs and tropical cyclones, including peak wave height during the storm compared to ambient wave height, distance of the reefs from the coast, height of reef, continuity of reefs, tidal conditions etc. (Roeber and Bricker, 2015) These factors were inadequately captured by the global statistical datasets available to us. However, Beck et al. (2018), using a very different, process based, hydrodynamic approach were able to estimate the flood protection benefits provided by global coral reefs. They estimated these services at about $3 billion/yr for 30 countries. However, Australia, with one of the largest coral reefs in the world, was not included in that study. This is because coral reefs in shallow water close to populated coasts provided the largest flood protection and the Great Barrier Reef is far offshore and not proximal to large population centres.

As Fig. 5 shows, there is still significant unexplained variation in the results. The effects of tropical cyclones on property damages are complex. However, our Bayesian R^2 of 0.49 shows our model captures a large portion of the variability in damages globally using data across 61 countries/regions and over 75 years. Our results clearly indicate and quantify the major effects that coastal wetlands have on moderating damage from tropical cyclones.

Next, we estimated in a similar way *deaths/population* using Equation (1) as a log–log function of wind speed of the storm (*windspeed*), forward speed of the storm (*speed*), wetland area in the swath of the storm (*wetlands*), volume of water in the ocean proximal to the landfall (*volume*) and a linear function of year of the storm −1900 (*time*). Results for these parameters are given in Fig. 6 and Table 3. For this analysis we used the entire dataset back to 1902, since earlier storms were much more likely to report deaths accurately than damages and many storms with missing damage data did report deaths. This left us with 936 storms that reported deaths.

The Bayesian R^2 for this model is 0.47. Fig. 7 is a plot of predicted deaths vs. observed values for the 936 storms included in this analysis

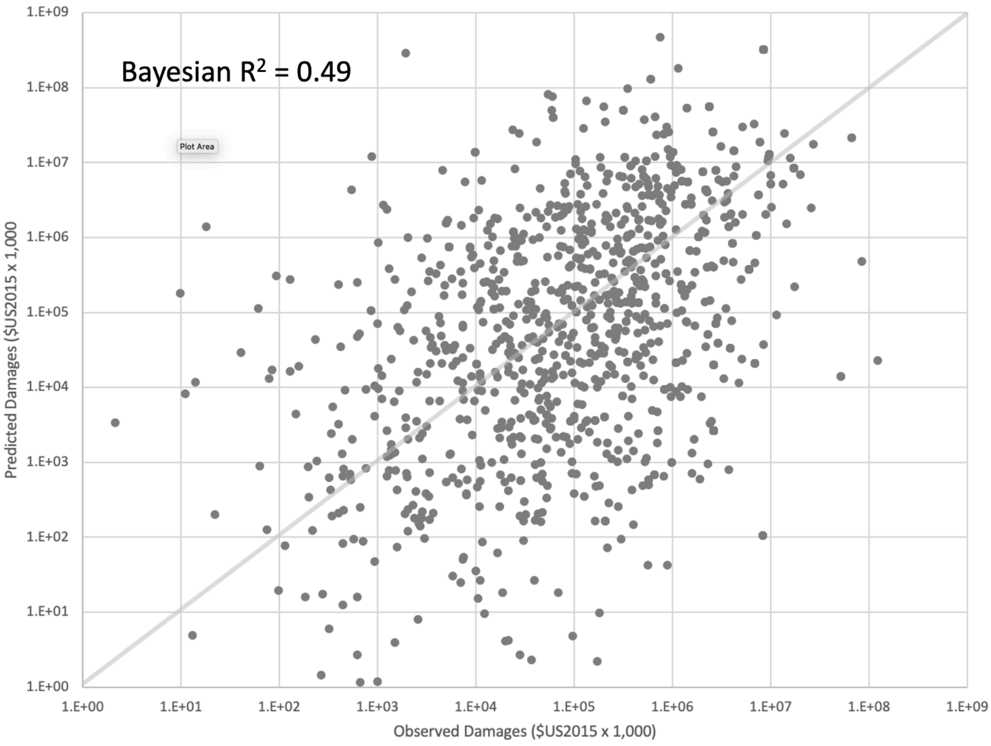

Fig. 5. Predicted (based on median coefficient values) vs. observed damages for the 673 storms included in the analysis.

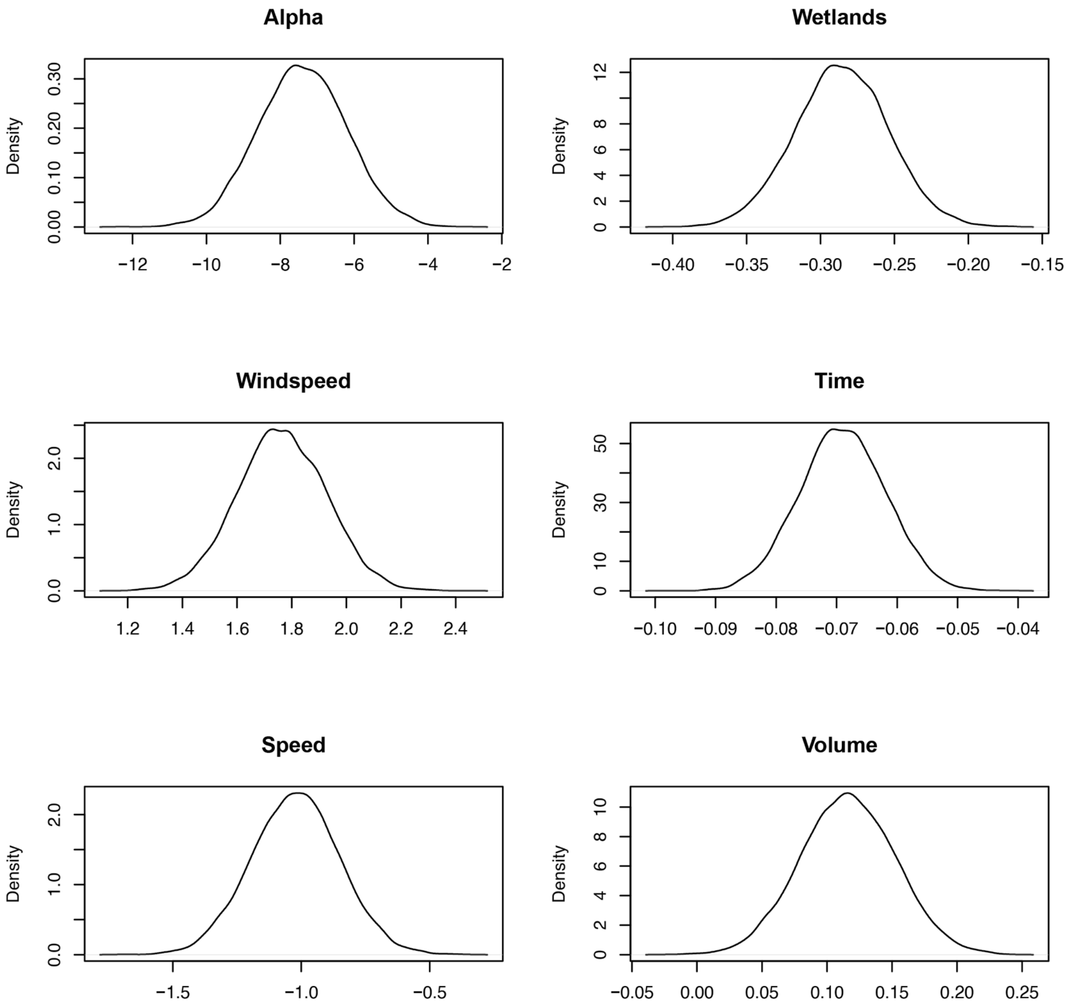

Fig. 6. Marginal posterior distributions of parameter estimates for the deaths/population model using Eq. (1).

Table 3
Parameter estimates and 95% highest posterior density credibility intervals for the model with deaths/population as the dependent variable.

$$\ln\left(\frac{deaths}{Population}\right) = -7.402 - 0.286\ln(wetlands+1) + 1.762\ln(windspeed) - 1.021\ln(speed) + 0.115\ln(volume) - 0.069\bullet(\text{time})$$

	α	*wetlands*	*windspeed*	*speed*	*volume*	*time*
2.5%	−9.698	−0.348	1.446	−1.359	0.045	−0.083
Median	**−7.402**	**−0.286**	**1.762**	**−1.021**	**0.115**	**−0.069**
97.5%	−5.041	−0.224	2.082	−0.684	0.188	−0.055
p-values	< 0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.001

where predicted deaths represent the median values for deaths from the joint posterior distribution (which includes estimates for population at the time of the storm).

We see similar results for our model in estimating the deaths from tropical cyclones as we did for estimating property damages. The influence of wetlands is again very significant (Table 3) in avoiding deaths and the other variables have similar influences. As far as we know, this is the first quantitative estimate of the relative influence of coastal wetlands on lives lost from tropical cyclones. Our results clearly indicate that coastal wetlands have a major influence on saving lives.

Our models do not accurately predict the damages or lives lost from specific storms, due to the complexity of this relationship. However, they do very well at estimating the overall relationship between wetlands and damages and deaths, allowing us to estimate the value of coastal wetlands in avoiding those damages and deaths.

4. Annual damages avoided and lives saved

Next, we use these results to estimate: (1) the spatial distribution of avoided damages and lives saved; and (2) the annual value of coastal wetlands for storm protection globally and by country/region.

To do this, we needed to know the probabilities of particular locations being hit by a tropical cyclone of a given magnitude in a typical year. We estimated this probability based on historical storm frequency by storm category striking 100 × 100 km pixels (Fig. 3). We then applied equations 4a-c in Supplementary Materials and Methods to each 100 × 100 km pixel globally to produce maps of the value of coastal wetlands for storm protection in terms of both avoided property damages (Fig. 8) and lives saved (Fig. 9).

Summing over all pixels with a chance of being hit by a tropical cyclone yielded an estimate of global avoided damages. Fig. 10 is a probability density plot for this estimate, with a median value of $447 billion/yr (2015$US), a mean of $475 billion/yr and a 90% centralized credibility interval (from the joint posterior distribution) of $213–$837 billion/yr

For global lives saved, this resulted in the probability density plot shown in Fig. 11, with a median value of 4620 lives saved, a mean of 4720 lives saved, and a 90% centralized credibility interval (from the joint posterior distribution) of 3230–6550 lives saved.

We then summed these values for each of the 71 countries/regions hit by tropical storms. Table 4 shows the number of tropical cyclones,

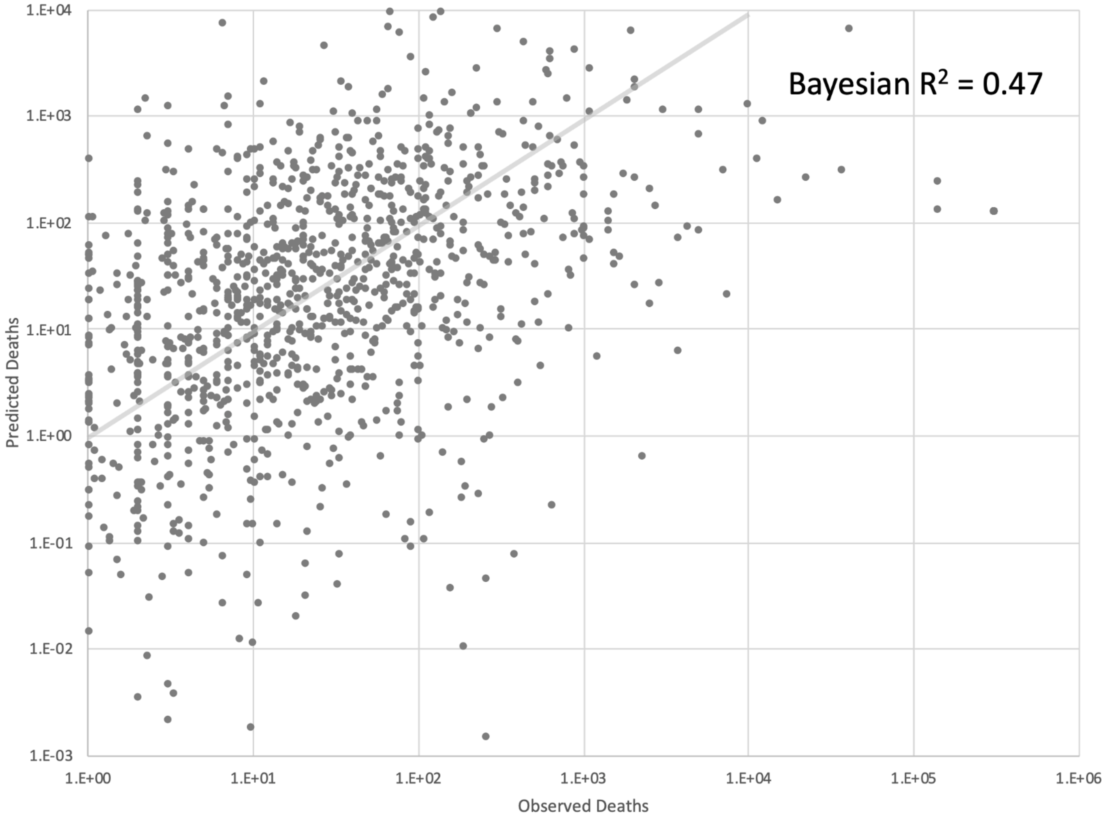

Fig. 7. Predicted vs. observed deaths for the 936 storms included in this analysis.

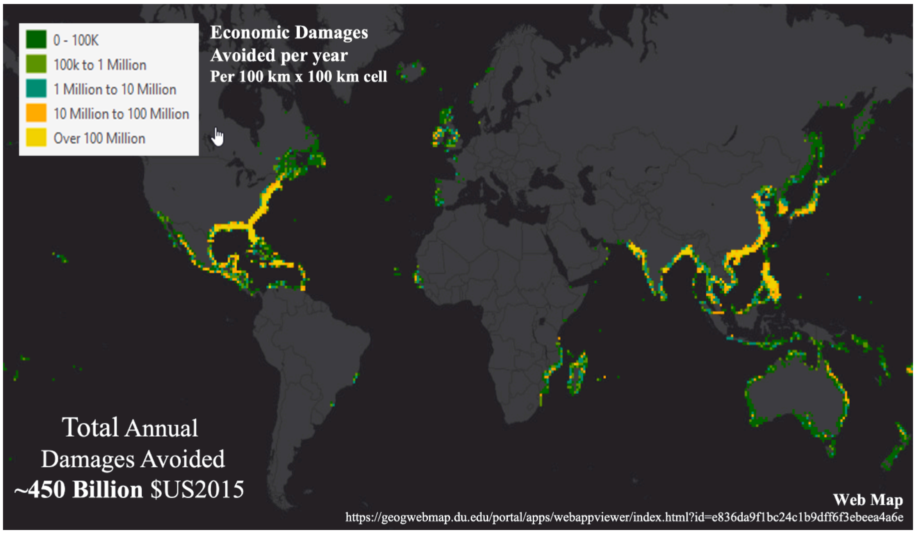

Fig. 8. Spatial distribution of avoided damages per year by coastal wetlands from tropical cyclones.

total historical damages and lives lost due to tropical cyclones, and the annual estimated avoided damages and lives saved by coastal wetlands for each country/region. Note that the distribution of storm protection across countries/regions is quite variable, and is dependent on storm probability, GDP in storm prone areas, coastal wetlands in storm prone areas, and coastal bathymetry. The top five countries in terms of annual avoided damages (all in 2015$US) are United States ($200 billion), China ($157 billion), Philippines ($47 billion), Japan ($24 billion), and Mexico ($15 billion). In terms of annual lives saved, the top five are China (1309), Philippines (976), United States (469), India (414), and Bangladesh (360).

5. Discussion

These results are a significant expansion and improvement over previous estimates of the value of coastal wetlands for storm protection. Our analysis maps the global distribution of these benefits. The summaries by country/region can help guide policy decisions about coastal wetland conservation and restoration.

Table 5 summarizes the results from some previous studies for comparison. Most are statistical analyses limited to single countries/regions using much smaller sample sizes. For example, Farber (1987) looked at a subnational region (Louisiana) and specific damages (wind)

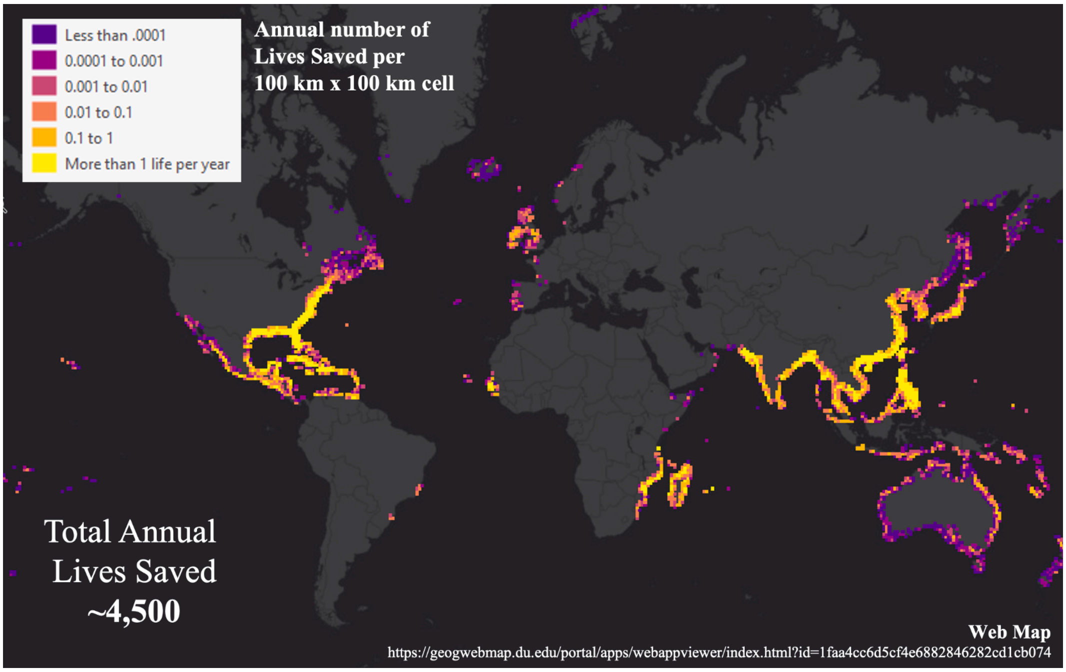

Fig. 9. Spatial distribution of lives saved per year by coastal wetlands from tropical cyclones.

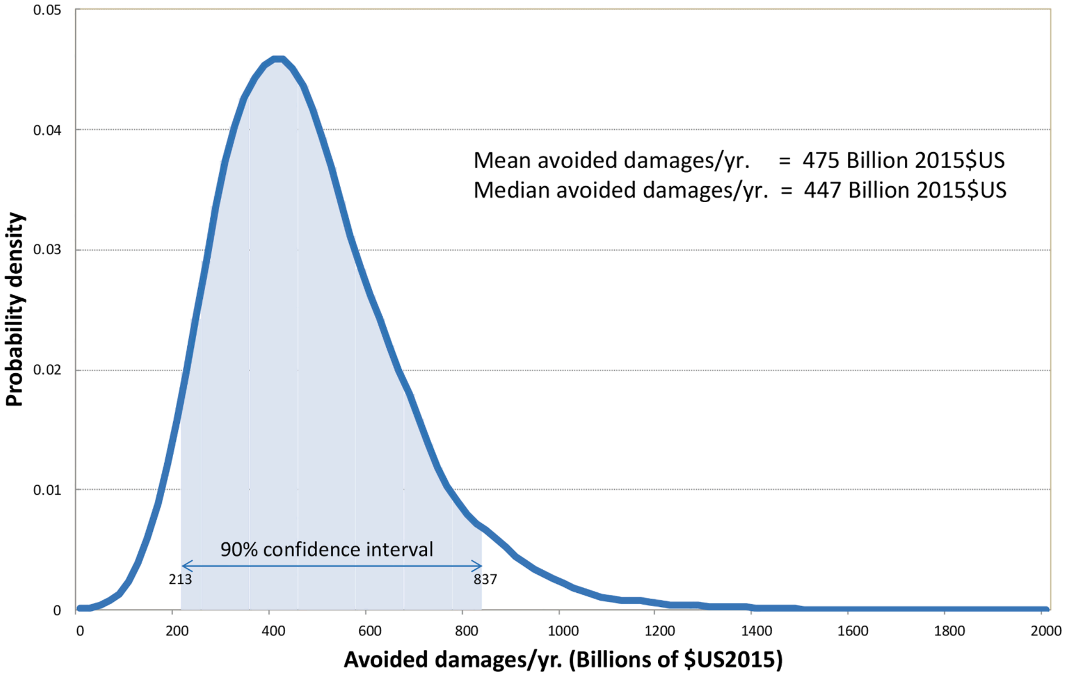

Fig. 10. Probability density plot for global avoided damages from tropical cyclones by coastal wetlands.

from a small number of storms. Later studies employed larger sample sizes and better data on damages, wetland area, and storm characteristics. Our estimates are based on a much larger global sample, but they are consistent with the other studies. For example, Sun and Carson (2020) produced an average estimate of $US 18,000/ha/yr for the US, a bit larger than our global average of $US11,000/ha/yr. One might have expected the difference to be even larger as the average GDP/capita in the US is higher than the majority of countries impacted by tropical cyclones. But our total value for the US of $US 200 billion/yr (Table 4) is consistent with the results from Sun and Carson (2020) and damages from tropical cyclones are not directly related to national GDP/capita. Menéndez et al. (2020) estimated the global value of mangrove forests for flood protection using a totally different, process-based hydrodynamic approach. Their approach provides some of the underlying causality for the statistical results we observe, and their value estimates for avoided flooding damages provided by mangrove forests are consistent with what we observe. Our statistical analysis includes all coastal wetlands (not just mangroves) and includes all damages from the storms (not just flood damages).

All of the studies mentioned are spatially explicit and show a broad range of values depending on the local infrastructure at risk, wetland area in the swath, building codes that affect damages, the probability of

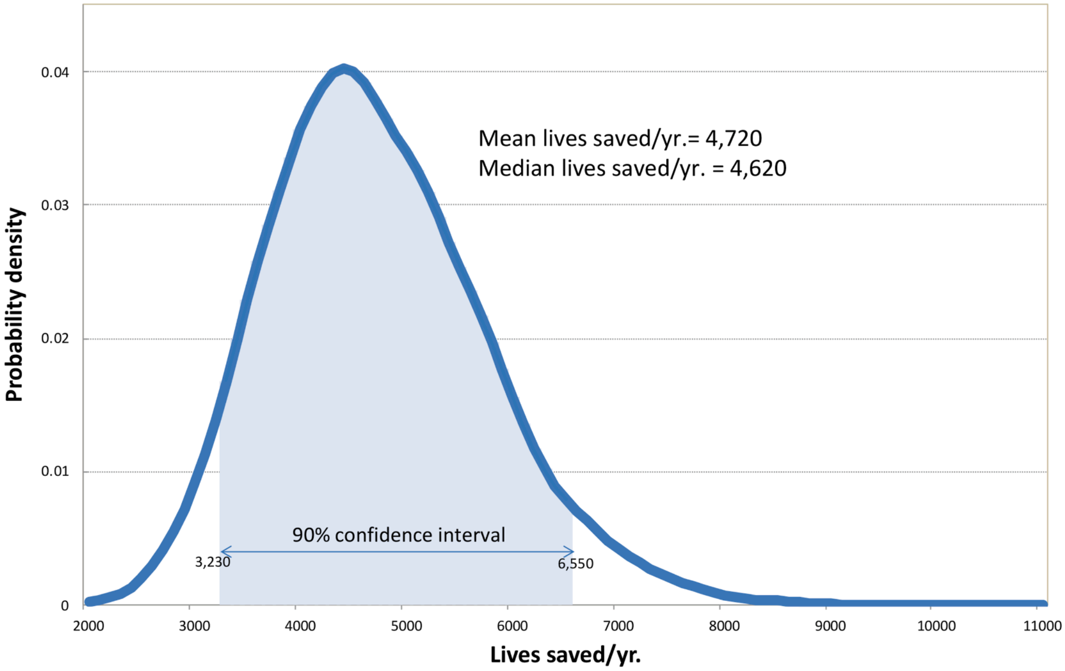

Fig. 11. Probability density plot for global lives saved from tropical cyclones by coastal wetlands.

experiencing tropical cyclones of different intensities, and other factors. But in general, high valued wetlands occur where there are high storm probabilities, large coastal infrastructure to be protected, and large areas of wetlands to do the protecting.

Ours is the first estimate globally and for all countries/regions affected by tropical cyclones of the value of all coastal wetlands for avoiding all tropical cyclone damages and the first estimate of the global value of wetlands for avoiding lives lost from tropical cyclones.

Globally, tropical cyclone intensity has been increasing in recent decades due to an increase in tropical cyclone potential caused by an increase in ocean surface temperatures. (Emanuel, 2020; Kossin et al., 2020). For example, the number of tropical cyclones in the Atlantic basin alone in 2020 was a new record of 30 named storms, with 7 registering winds of 100 knots or more. These trends are consistent with Vecchi et al. (2013) and Smith et al. (2010) who show increasing frequency over time in the Atlantic basin. Other studies show that while major tropical cyclones (categories 4–5) are becoming increasingly frequent (Emanuel, 2020; Klotzbach and Landsea, 2015; Kossin et al., 2020) hurricane categories 1–3 appear to have remained relatively constant. Klotzbach et al. (2018) found that the number of landfalls in the US has not been increasing over the period 1900 to 2015, even though damages increased dramatically. However Weinkle et al. (2018) did not find any clear trends in hurricane damages for the US.

Most of these studies were limited to the Atlantic basin or the US. Fig. 12 shows the *global* trends for tropical cyclones included in IBTrACS v3 (https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00834) for (1) all tropical cyclones; and (2) for those that have recorded damages or deaths in EM-DAT and were included in our database. These plots show a clear change in the trends post 1940, due, we believe, to better reporting after that date, especially for damages. This is why we only used the post 1940 tropical cyclones that recorded damages from EM-DAT for our damages model. If pre 1940 storms are excluded, the R^2 for the trend line increases from 0.77 to 0.83.

While not all basins show increasing tropical cyclone frequency, recent global trends are clear. Climate change will continue to exacerbate these trends and will make the value of coastal wetlands for storm protection and their other ecosystem services even greater. This is also becoming increasingly relevant as 700 million people (approximately 10% of the human population) currently live at <10 m above sea level on an area that is 2% of the land surface (McGranahan et al., 2007). The increasing vulnerability of aging coastal built infrastructure in the face of climate change also highlights the need to protect and restore coastal wetlands.

Coastal wetlands provide ‘horizontal levees’ that are maintained by nature and are far more cost-effective than constructed levees or seawalls (Liu et al., 2019). Coastal wetlands also provide a host of other valuable ecosystem services that constructed levees do not. They have been estimated to provide about $US 135,000/ha/yr of other ecosystem services over and above storm protection (Costanza et al., 2014). Experience (including the current study) has shown that as we better understand the functioning of ecological systems and their connections to human wellbeing, estimates of their values tend to increase. At the same time land use change, including the loss of coastal wetlands, is reducing the extent and total value of the ecosystem services they are able to provide (Costanza et al., 2014). It has been estimated that since 1900 the world has lost over 50% of wetlands (Davidson, 2014). Reversing these trends and investing in the maintenance and restoration of coastal wetlands is an extremely cost-effective strategy for society and can significantly increase sustainable wellbeing for humans and the rest of nature (Kubiszewski et al., 2017).

6. Limitations and caveats

- As noted, the interaction between tropical storms and coastal wetlands is complex. Our analysis does not attempt to model the biophysical dynamics of this interaction, as some other recent studies have done (Beck et al., 2018; Menéndez et al., 2020). We are only looking at statistical relationships between the variables for which we were able to collect sufficient data globally. For example, the relative position of infrastructure and population relative to the storm swath and direction is not used in the analysis – only the aggregate area of wetlands, infrastructure, and total population in

Table 4
Estimates of number of tropical cyclones, area of coastal wetlands in swaths, property damage and deaths, and the value of coastal wetlands for protection against damages and deaths per year by country/region from tropical cyclones.

Country/ Region	Total Number of Storms in Country	Total Number of Landfalls in Country	Total Area of Wetlands in Swaths (ha) in Country	GDP in Swaths at the time of the Storms in Country (2015$US x 1,000)	Total Damages from Storms in Country (2015$US x 1,000)	Population in Swaths at time of Storms in Country	Total Deaths from Storms in Country	Estimated Avoided Damages per year (2015$US x 1,000)	Estimated Lives Saved per year
Anguilla	1	1	3,258	$9,009	$280,350	22,013	5	$61,602	0.607
Antigua and Barbuda	6	6	16,551	$536,236	$933,500	228,647	9	$49,852	0.545
Australia	24	37	1,814,121	$176,860,873	$15,247,149	5,062,004	127	$1,120,757	8.021
Bahamas	12	17	582,579	$40,344,276	$9,481,209	825,476	417	$921,472	3.336
Bangladesh	42	45	4,671,934	$254,252,427	$8,256,515	487,954,491	556,861	$5,232,920	360.082
Barbados	2	2	54	$72,435	$4,320	16,100	57	$1,375	0.017
Belize	5	5	104,778	$473,353	$1,310,620	414,869	1,826	$536,887	5.301
Bermuda	2	2	1,728		$491,500	54,074	4	$302	0.152
Brazil	1	1	9,630	$6,377,183	$437,500	595,700	4	$14,904	0.245
Canada	4	5	494,117	$8,920,685	$1,179,051	1,013,634	87	$173,095	1.366
Cape Verde	2	2	1,296	$43,727	$8,480	60,041	12	$1,999	0.085
Cayman Islands	1	1	1,620	$1,362	$660	0	0	$225,601	0.392
China	98	126	1,811,286	$10,249,509,956	$83,709,713	1,632,867,152	8,703	$156,621,877	1,309.023
Comoros	1	1	351	$173,790	$54,740	158,336	33	$1,666	0.112
Cuba	19	20	1,336,230	$163,306	$9,951,850	16,089,716	4,965	$28,225	74.815
Dominica	3	3	20,430	$656,730	$1,685,320	63,248	2,064	$39,120	3.323
Dominican Republic	10	10	774,486	$8,647,037	$4,067,208	29,934,474	3,902	$4,935,033	56.389
El Salvador	1	1	33,606	$0	$0	2,672,195	4		
Micronesia	1	1	20,619	$3,465	$11,000	36,731	5	$733	0.134
Fiji	23	27	350,532	$7,776,785	$1,472,771	2,601,908	258	$183,586	2.035
Grenada	1	1	243	$85,093	$1,111,250	57,798	39	$2,522	0.047
Guadeloupe	3	3	12,501	$489	$95,500	338,491	2,019	$0	0.000
Guatemala	1	1	28,953	$208,172	$708,500	3,593,737	174	$131,625	5.586
Haiti	18	18	1,377,809	$2,341,727	$3,860,150	31,245,246	7,127	$514,820	43.790
Honduras	6	6	160,983	$119,720	$140,580	3,285,241	29	$147,617	5.439
Hong Kong	2	2	24,372	$672,047	$418	31,863,451	4		
India	62	87	1,539,863	$284,030,309	$25,044,622	359,203,013	70,822	$8,700,406	414.099
Indonesia	1	1	1,872	$0	$0	697,657	11	$107,040	4.608
Iran	1	1	18	$0	$0	61,852	12	$1	0.000
Ireland	2	2	366,110	$9,723,570	$1,510	4,112,504	13	$37,587	0.326
Jamaica	10	12	72,648	$3,135,115	$2,547,952	3,538,983	510	$1,103,939	12.888
Japan	61	93	676,710	$8,954,621,088	$53,371,953	738,302,793	9,629	$23,531,915	128.356
Madagascar	37	62	1,345,869	$4,470,372	$4,374,732	25,819,794	1,822	$264,170	32.386
Martinique	3	3	6,111	$3,910	$342,000	748,839	4		
Mauritius	4	4	3,087	$10,804,479	$1,670,739	1,020,746	16	$185,774	2.332
Mexico	54	84	2,418,138	$219,688,500	$27,178,977	57,145,524	4,477	$14,667,992	72.625
Morocco	1	1	0	$1,204,282	$61	3,071,257	1	$0	0.000
Mozambique	12	14	1,075,319	$4,173,960	$425,130	6,987,602	517	$63,180	11.077
Myanmar (Burma)	10	10	234,666	$30,382,504	$4,528,730	10,156,221	143,359	$548,886	26.829
New Caledonia	5	5	154,197	$7,393	$71,502	276,715	8	$66	0.715
New Zealand	1	1	27,387	$0	$0	319,112	50	$58,652	0.586
Nicaragua	8	12	360,900	$9,861,726	$1,458,763	6,525,975	445	$33,960	1.384
North Korea	6	6	10,431	$59,226	$8,302,980	25,801,755	143	$19	1.838
Northern Mariana Islands	1	1	0	$0	$0	30,018	2	$46	0.003
Oman	3	3	18	$588,746	$1,156,000	343,764	37	$2,107	0.014
Pakistan	2	2	448,775	$15,102,089	$102,729	18,031,520	254	$198,734	5.303
Philippines	185	221	7,021,494	$1,468,801,256	$24,915,915	564,559,443	39,764	$46,823,874	976.444
Portugal	1	1	5,715	$117,070,382	$108,570	4,506,721	2	$25,647	0.277
Puerto Rico	9	9	118,260	$57,985,509	$71,114,500	13,647,157	614	$6,767,795	19.561
Réunion	4	4	1,656	$88,976	$99,680	908,296	199	$672	0.873
Saint Kitts and Nevis	2	2	2,160	$201,955	$638,788	52,957	5		
Saint Lucia	4	4	3,555	$180,299	$301,565	232,630	23	$40,216	2.098
Saint Martin	1	1	1,638	$144,201	$3,977,000	87,272	7		
St. Vincent & Grenadines	3	3	1,656	$409,495	$52,847	8,142	4		
Samoa	1	1	612	$904,197	$136,990	135,458	12	$1,439	0.031
Solomon Islands	5	6	66,825	$25,665	$43,200	100,982	119	$2,021	0.291
Somalia	1	1	288	$0	$0	48,811	30	$10	0.027
South Korea	19	26	116,532	$589,942,812	$12,459,966	184,755,514	1,853	$4,841,590	26.025
Sri Lanka	3	3	8,244	$3,277,283	$699,620	4,387,509	772	$129,640	3.795

(*continued on next page*)

Table 4 (*continued*)

Country/ Region	Total Number of Storms in Country	Total Number of Landfalls in Country	Total Area of Wetlands in Swaths (ha) in Country	GDP in Swaths at the time of the Storms in Country (2015$US x 1,000)	Total Damages from Storms in Country (2015$US x 1,000)	Population in Swaths at time of Storms in Country	Total Deaths from Storms in Country	Estimated Avoided Damages per year (2015$US x 1,000)	Estimated Lives Saved per year
Taiwan	43	49	921,069	$5,916,300	$5,193,601	163,491,816	1,708	$3,531	330.612
Thailand	1	1	738	$774,885	$7,400	103,021	152	$590,252	9.731
Tonga	3	5	972	$7,364	$86,272	8,284	7	$1,049	0.057
Trinidad and Tobago	4	4	14,490	$5,805,743	$311,333	353,426	39	$185,720	1.051
Turks and Caicos Islands	1	1	55,917	$24,721	$11	0	0	$16,313	0.107
U.S. Virgin Islands	1	1	3,915	$1,651	$212,160	112,249	7		
United Kingdom	1	1	214,748	$82,176,838	$453,000	18,553,747	5	$101,020	0.933
United States	84	125	27,053,307	$3,740,622,190	$640,910,149	246,496,518	9,359	$200,515,675	469.236
Vanuatu	8	8	30,744	$50,646	$886,860	162,060	87	$9,889	0.464
Venezuela	1	1	93,762	$272,538	$7,380	3,007,178	100	$821	2.313
Vietnam	55	61	467,208	$220,629,553	$7,502,963	133,279,871	15,842	$2,279,446	112.498
Yemen	1	1	0	$0	$0	60,489	25	$1	0.000
Totals	1,014	1,288	58,601,692	$26,601,421,613	$1,045,198,005	4,852,309,966	891,602	$482,788,685	4,553

Table 5
Estimates of the average value of coastal wetlands for storm protection from some previous studies compared with the current study.

Source	Location	Storm protection value (2015$US/ha/yr)	Damages included	Coastal Ecosystems included	Modelling Approach
(Farber, 1987)	Louisiana	1300	Wind	Marshes	Statistical
(Barbier, 2007)	Thailand	6700	All	Mangroves	Statistical
(Costanza et al., 2008)	USA	9400	All	Marshes	Statistical
(Liu et al., 2019)	China	13,000	All	All	Statistical
(Menéndez et al., 2020)	Global	4900	Flooding	Mangroves	Hydrodynamic
(Sun and Carson, 2020)	USA	18,000	All	All	Statistical
(Mulder et al., 2020)[a]	Australia	3200	All	All	Statistical
This Study	**Global**	**11,000**	**All**	**All**	**Statistical**

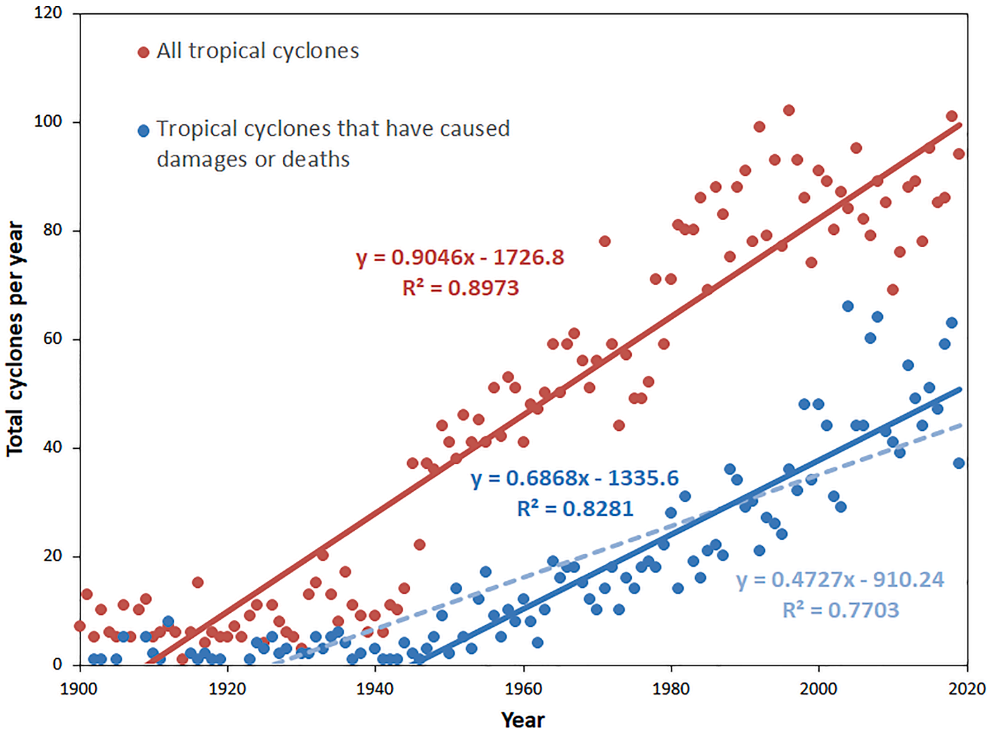

Fig. 12. Worldwide annual tropical cyclones in all basins (tropical storms and category 1–5 storms on the Saffir scale) since 1900 (from IBTrACS v3) and total number of tropical cyclones that have caused damages or deaths (from EM-DAT) and that that were used in our analysis . Dashed blue trend line is for all storms from 1900. Solid blue trend line is for storms post 1940. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the swath. Thus we are demonstrating statistical, not deterministic or causal relationships. It is interesting, however, that these different approaches give similar results as to the value of coastal wetlands for storm protection, leading to more confidence in the results of both.

- Global data on land cover, GDP, storm tracks, wind speed and storm speed, property damages, and lives lost are all uncertain in different ways. Combining these data introduces additional uncertainty. Our Bayesian approach is better able to deal with this data uncertainty and give us better estimates of the range of uncertainty in the results, but better data would obviously help and we had to make several assumptions in order to complete the analysis. For example, we back-cast GDP in the swath based on GDP in the swath in 2015 (for which we have reasonably accurate data) and the ratio of GDP in the country/region in 2015 to GDP in the country/region in the year of the storm (for which we also have reasonably accurate data from a different source). But this ignores differential GDP growth rates in different parts of countries/regions. Likewise, we used global coastal wetland area data from the ESA CCI land cover time series, but this series showed negligible change in wetland area from 1980 to present, even though we know that coastal wetlands have declined in many areas over that time period. We ran some sensitivity analyses to see what difference this makes to our results (see Supplementary Materials and Methods). It turned out to be negligible, but obviously we would like to have better global wetland area data over time. In addition, damage data is quite unreliable in its coverage for tropical cyclones in the first half of the 20th century, especially for smaller losses prior to 1980. We limited our damage model to post-1944 storms for this reason.
- Another issue is the shape and size of the swath we used. We compared two different ways of doing this (see Supplementary Materials and Methods) and noted that they gave similar results, but each of these (or any other method we might have chosen) represents an assumption on our part about the area over which the storm has its major impacts. The fact that our two different methods had similar results implies that our analysis is relatively robust to this assumption.

7. Data availability

All data used in this analysis is available as an Excel file in Supplementary Data. In addition a story map describing the process is available at https://storymaps.arcgis.com/stories/4be8afd6872145f585782f6e3f8fbe95.

Funding

This research received no external funding.

CRediT authorship contribution statement

Conceptualisation, RC and All; Data collection and formatting, SA, PS, IK, XW; Bayesian analysis, OM, KM. Additional analysis, PS, XL, OPM, MLM, DJ, GD; Writing—original draft preparation, RC; review and editing, All. All authors have read and agreed to this version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We gratefully acknowledge the support of our institutions during the preparation of this manuscript, and the helpful comments of 3 anonymous reviewers on earlier drafts. The manuscript was the result of frequent Zoom meetings during the 2020-21 Covid19 Pandemic.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102328.

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