nature climate change

LETTERS

PUBLISHED ONLINE: 26 FEBRUARY 2014 | DOI: 10.1038/NCLIMATE2120

Taming hurricanes with arrays of offshore wind turbines

Mark Z. Jacobson[1]*, Cristina L. Archer[2] and Willett Kempton[3]

Hurricanes are causing increasing damage to many coastal regions worldwide[1,2]. Offshore wind turbines can provide substantial clean electricity year-round, but can they also mitigate hurricane damage while avoiding damage to themselves? This study uses an advanced climate–weather computer model that correctly treats the energy extraction of wind turbines[3,4] to examine this question. It finds that large turbine arrays (300+ GW installed capacity) may diminish peak near-surface hurricane wind speeds by 25–41 m s^{-1} (56–92 mph) and storm surge by 6–79%. Benefits occur whether turbine arrays are placed immediately upstream of a city or along an expanse of coastline. The reduction in wind speed due to large arrays increases the probability of survival of even present turbine designs. The net cost of turbine arrays (capital plus operation cost less cost reduction from electricity generation and from health, climate, and hurricane damage avoidance) is estimated to be less than today's fossil fuel electricity generation net cost in these regions and less than the net cost of sea walls used solely to avoid storm surge damage.

Hurricane damage is increasing with expanding coastal development[1] and rising sea levels[2]. Increasing temperatures may also increase hurricane intensity, but it is uncertain whether hurricane intensity changes so far have exceeded natural variability[5].

Continuing a long-term problem of hurricane damage, Hurricane Sandy in 2012 caused ∼$82 billion in damage to three US states[6] and 253 fatalities in seven countries. Hurricane Katrina destroyed much of New Orleans, Louisiana. Following Hurricane Sandy, sea walls were proposed to protect cities from hurricane storm surge. Such walls might cost $10–$29 billion for one city[7], protect the areas only right behind the walls, and limit the access of populations to coastal zones. Large arrays of wind-wave pumps, which bring deep, cool water to the surface have also been proposed to reduce hurricane intensity[8]. This technology also serves one purpose.

This study quantitatively tests whether large arrays of wind turbines installed offshore in front of major cities and along key coastal areas can extract sufficient kinetic energy from hurricane winds to reduce wind speed and storm surge, thus preventing damage to coastal structures as well as to the offshore turbines themselves. Unlike sea walls, offshore wind turbines would reduce both wind speed and storm surge and would generate electricity year-round.

The hypothesis is tested here through numerical simulations with GATOR–GCMOM, a global-through-local climate–weather–air-pollution–ocean forecast model[3,4] (Supplementary Information). The model extracts the correct amount of energy from the wind at different model heights intersecting the turbine rotor[3] given the instantaneous model wind speed, which is affected by turbulence and shear due to the hurricane and turbine itself (Supplementary Section 1.H). Several three-dimensional computer simulations without and with wind turbines were run for hurricanes Katrina and Isaac (US Gulf Coast) and Sandy (US East Coast; Methods and Table 1).

Figure 1 compares modelled with observed storm tracks and peak near-surface wind speeds for hurricanes Katrina, Sandy and Isaac. Model results include those from GATOR–GCMOM and two operational hurricane models (Geophysical Fluid Dynamic Laboratory (GFDL) and Hurricane Weather Research and Forecasting (HWRF)). The GATOR–GCMOM modelled tracks followed observed tracks, particularly for Katrina and Isaac. For Katrina, GATOR–GCMOM-modelled peak wind speeds and their rates of change with time were similar to observed peak winds and slightly more accurate than those from the GFDL model. For Sandy, GATOR–GCMOM-modelled peak winds slightly exceeded observed values, but 'its results are comparable with those of the other operational and semi-operational models (T. Marchok, NOAA/GFDL, personal communication).

Supplementary Fig. 6 shows results from a case where turbine arrays were added offshore of Cuba and from Florida to Texas during Hurricane Katrina (Simulation A). Such arrays, in comparison with the base-case simulation of Katrina without turbines, reduced wind speeds by up to 41 m s^{-1} (92 mph) at 15 m height and by up to 80 m s^{-1} (179 mph) at the 100 m hub height typical of an offshore wind turbine while producing 1.1 TW of power. For Simulation E, where turbine arrays were placed along most of the East Coast during Hurricane Sandy, turbines reduced 15 m wind speeds up to 39 m s^{-1} while extracting up to 2.65 TW (Table 1, Supplementary Fig. 7). The greater modelled power extraction during Sandy was due to the larger radius of hurricane-force winds, a factor also observed[9].

Figure 2 and Supplementary Fig. 8 show the two-dimensional time evolution of several parameters with and without turbines just to the southeast of New Orleans during Hurricane Katrina (Simulation D). Without turbines, the strongest winds when the hurricane was close to landfall were on the eastern side of the core (Supplementary Fig. 8), consistent with observations. With turbines, the hurricane dissipated faster.

Comparisons of Simulation D with A for Katrina and of Simulation H with E for Sandy indicate that wind speed reductions and power extraction were similar in the overlapping regions of turbines whether the turbines were just upstream of the region of interest or along much of the coast (Supplementary Fig. 9). Thus,

---

[1]Department of Civil and Environmental Engineering, Stanford University, Stanford, California 94305-4020, USA, [2]College of Earth, Ocean, and Environment, University of Delaware, Newark, Delaware 19716, USA, [3]College of Earth, Ocean, and Environment, and Department of Electrical and Computer Engineering, University of Delaware, Newark, Delaware 19716, USA. *e-mail: jacobson@stanford.edu

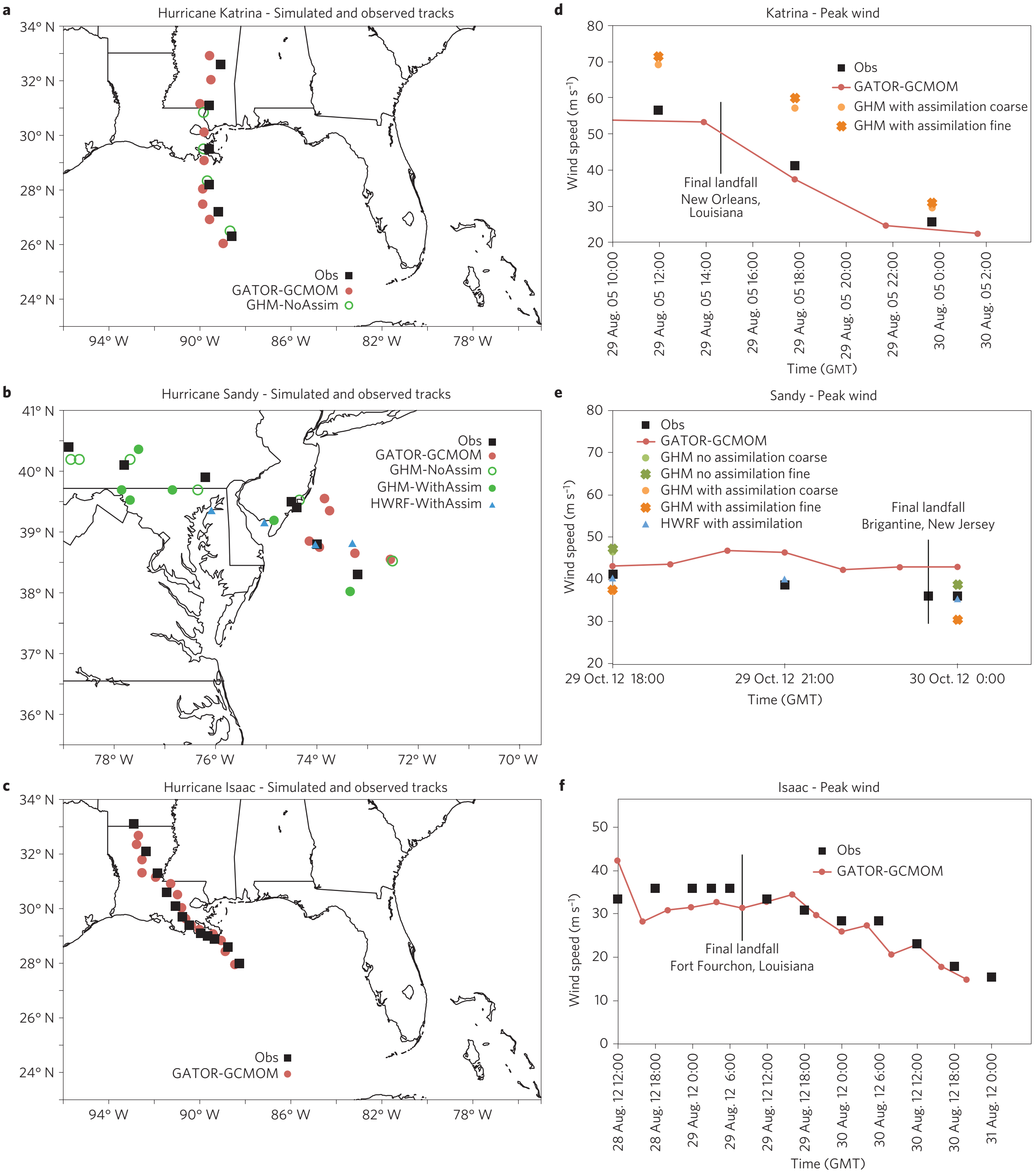

Figure 1 | Modelled versus observed tracks and peak surface wind speeds for Hurricanes Katrina, Sandy, and Isaac. a–f, Modelled versus observed[21–24] tracks (**a**–**c**) and peak near-surface wind speeds (**d**–**f**) of hurricanes Katrina (**a**,**d**), Sandy (**b**,**e**) and Isaac (**c**,**f**). GATOR-GCMOM: present model. GHM with assimilation: operational GFDL Hurricane Model[25] in which observations are assimilated and run at coarse (0.167° × 0.167°) and fine (0.083° × 0.083°) resolutions. GHM without assimilation: ensemble member runs of GHM without data assimilation on the same grids, available for Sandy alone. HWRF: HWRF model[26] run with data assimilation on a 0.03° × 0.03° grid. Results were available for Sandy alone. The GATOR-GCMOM modelled Katrina track was from 18:00 GMT 28 August 2005–02:00 GMT 30 August 2005, and results are shown every four hours. The observed track was from 18:00 GMT 28 August 2005–00:00 GMT 30 August 2005. The GATOR-GCMOM-modelled track for Sandy is shown hourly 18:00 GMT 29 October 2012–00:00 GMT 30 October 2012. The observed track is from 18:00 GMT 29 October 2012–00:00 GMT 31 October 2012. The GATOR-GCMOM-modelled track for Isaac is shown every four hours from 12:00 GMT 28 August 2012–20:00 GMT 30 August 2012. The observed track is shown every six hours from 12:00 GMT 28 August 2012–00:00 GMT 31 August 2012.

Table 1 | Characteristics of the turbine simulations discussed and summary of modelled peak power extraction, wind speed reduction, and storm surge reduction for each simulation.

	Katrina				Sandy				Isaac
	(A) *Most of Gulf Coast	(B) *Most of Gulf Coast	(C) *Most of Gulf Coast	(D) *New Orleans alone	(E) *Much of East Coast	(F) *Much of East Coast	(G) *Much of East Coast	(H) *DC to NYC alone	(I) *New Orleans alone
†Turbine rated power (MW)	7.58	7.58	7.58	7.58	7.58	7.58	5.0	7.58	7.58
Cutout wind speed (m s^{-1})	50	50	34	50	50	50	50	50	50
Spacing area (A; m^2)	$28D^2$	$56D^2$	$28D^2$	$28D^2$	$28D^2$	$56D^2$	$28D^2$	$28D^2$	$28D^2$
Installed density (W m^{-2})	16.78	8.39	16.78	16.78	16.78	8.39	11.25	16.78	16.78
Number of turbines	543,442	271,721	543,442	78,286	414,030	207,015	420,628	112,014	78,286
Nameplate capacity (TW)	4.119	2.060	4.119	0.593	3.138	1.569	2.103	0.849	0.593
‡Normal delivered power (TW)	1.53	0.766	1.53	0.221	1.17	0.583	0.893	0.316	0.221
§Peak extracted hurr. power (TW)	1.18	0.796	1.06	0.450	2.65	1.36	1.89	0.767	0.417
‖Peak 15-m wind decrease (m s^{-1})	−40.6	−44.1	−42.1	−36.1	−39.1	−35.1	−38.9	−36.0	−25.5
‡Storm surge reduction (%)	23–79	19–63	26–75	6–71	24–34	17–21	27–32	12–21	18–60

*All turbines were within 100 km of the coast. Gulf: 22.5°–32° N, 81.5°–95° W; New Orleans: 87.5°–89.5° W; East Coast: 35°–44° N, 65°–78° W; DC to NYC: 38.8°–41° N. †7.58 MW turbine is the Enercon E-126 (D = 127 m diameter rotor); the 5.0 MW turbine is from RE Power (D = 126 m). ‡Assumes mean annual Rayleigh-distributed hub-height offshore wind speeds of 8.5 m s^{-1} (refs 18,19) and the turbine power curve, without considering reduced winds due to power extraction by turbines. §This is the peak power extracted by wind turbines at any time during the simulation, accounting for reduced wind speeds due to extraction. ‖From model results, accounting for reduced wind speeds due to power extraction by turbines.

protecting a city may require arrays of turbines only upstream of the city.

Turbines in the New Orleans case (Simulation D) increased the central pressure in Katrina by >40 hPa as the hurricane eye moved over and past the turbine arrays (for example, Supplementary Fig. 8 at 14:00 GMT 29 August 2005). Turbines from Washington DC to New York City during Sandy similarly increased central pressure by up to ~5 hPa (Supplementary Fig. 10). Pressure increased for the following reason. Wind turbines were exposed first to the outer hurricane's rotational winds, which were slower than eye-wall winds, and the reduction in outer winds decreased wave heights there, decreasing surface friction. The angle at which cyclonic surface winds converge to the eye wall of a hurricane is governed by the balance among the pressure-gradient, Coriolis, apparent centrifugal and friction forces. The decrease in the friction force decreased convergence (winds become more circular, cyclonically), decreasing convection in the eye wall and divergence aloft above the eye wall, increasing central pressure. As turbine arrays first experienced and dissipated slower winds near them, thereby weakening the overall hurricane by increasing central pressure, the turbines themselves prevented nearby winds from reaching their maximum certified wind speed of 50 m s^{-1} (Fig. 2 and Supplementary Figs 8 and 9). The potential for turbine damage is an issue, but less so along the East Coast than the southern or Gulf coasts, even without turbine energy extraction, because hurricane intensity is weaker along the East Coast[10] (Supplementary Table 2).

Storm surge was assumed to be proportional to fetch (thus, storm size), the square of the wind speed (through wind stress) over the sector of the hurricane in which the wind is directed towards land, and the inverse of water depth (Supplementary Section 1.L). Offshore wind turbine arrays reduced storm surge by up to 34% for Sandy and 79% for Katrina, mainly owing to the average wind speed decreasing by up to 14% and 58% upwind of New York and New Orleans, respectively (Table 1 and Supplementary Fig. 9). The best place to locate offshore arrays for minimizing storm surge was directly upwind of a city itself. Results of a simulation (not shown) with wind farms to the south (where the hurricane core was coming from) rather than to the southeast (where the cyclonic flow was directly upwind, Simulation D) of New Orleans, led to storm surge reductions of only 14%.

Reducing turbine size from 7.58 MW (Simulation E) to 5 MW (Simulation G) for Sandy (Table 1) reduced nameplate capacity by 33% but peak output by only 24%. The reason is that the smaller turbines extracted less energy, thus back-row turbines received faster winds. For the same reasons, storm surge reduction was greater with larger turbines (Table 1).

Likewise, reducing the installed density of turbines by half (Simulation B versus A and Simulation F versus E in Table 1) reduced peak wind power extraction by 32% and 49%, respectively but decreased storm surge reduction from 23–79% to 19–63% for Katrina and from 24–34% to 17–21% for Sandy, suggesting that benefits are nonlinear with the number of installed turbines,

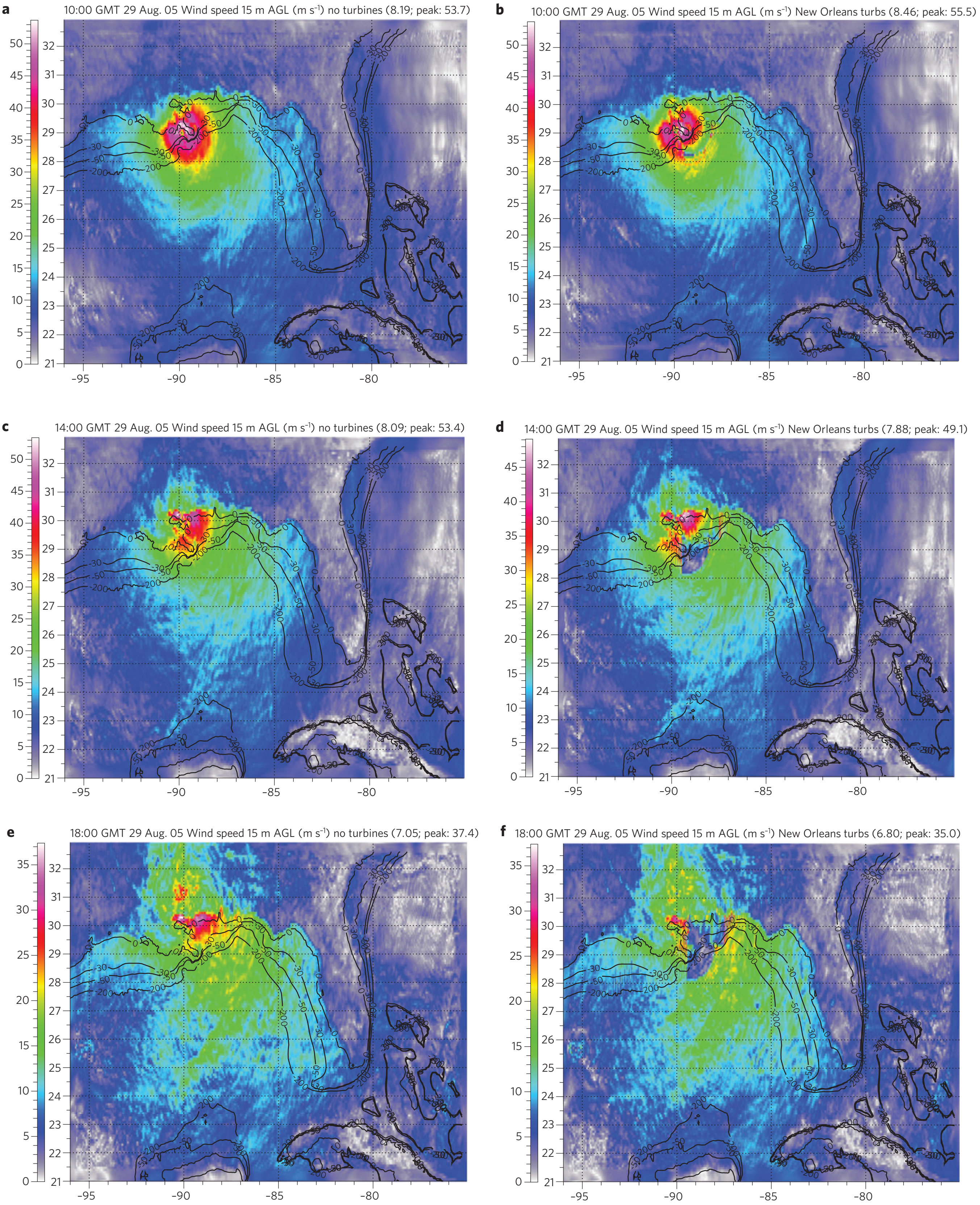

Figure 2 | Modelled surface wind speeds with and without turbines three times during Hurricane Katrina. a–f, 15-m wind speeds ($\mathrm{m\,s^{-1}}$) in the absence (**a**,**c**,**e**) and presence (**b**,**d**,**f**) of wind turbines offshore of New Orleans at three times near landfall during Hurricane Katrina based on simulations that were nested from the global to local scale (Simulation D in Table 1). The turbines assumed were Enercon E-126 7.58 MW turbines with rotor diameter (*D*) of 127 m and hub height of 100 m. Spacing was 4-D × 7-D, and turbines were placed within 100 km of shore in front of New Orleans between 87.5 and 89.5 W. The simulation was started at 18:00 GMT 28 August 2005, with the hurricane extant. The contours are bathymetry between 0 and 200 m depth.

Table 2 | Cost–benefit analysis of simulations D and H in Table 1, expressed in cents per kilowatt-hour.

	Katrina (D) New Orleans	Sandy (H) DC to NYC
*Wholesale cost of electricity (¢ kWh^{-1}) from offshore wind (best recent cost)	14.3	9.4
†Avoided health/climate losses (¢ kWh^{-1})	5.3	5.3
‡Avoided hurricane losses (¢ kWh^{-1})	0.21–0.68	0.09–0.13
Electricity cost minus benefit (¢ kWh^{-1})	8.3–8.8	3.9–4
§New generation electricity levellized cost with present fuel mix (¢ kWh^{-1})	10.5	10.5

*From ref. 11 with assumptions explained in text and Supplementary Information. Wind-electricity production cost is from ref. 11 for the East Coast and is scaled down for the Gulf Coast owing to lower wind speeds there and assuming the same turbine design in both locations (see Supplementary Information). †Ref. 12. ‡Assumes $81.2 billion in losses due to Katrina and $82 billion due to Sandy[6]. Low (high) avoided hurricane costs assume 4.1 (2.7) hurricanes for Katrina and 1.5 (2.3) for Sandy during the 30-yr (20-yr) lifetime of the turbines (Supplementary Information), mean annual Rayleigh-distributed wind speeds of 9 (8.5) m s^{-1}, and the power curve of an Enercon E-126 7.58 MW turbine, given in Supplementary Equation 5. Damage due to storm surge versus wind is apportioned 70:30, based on authors' judgement. Table 1 indicates a 6% (71%) modelled reduction in storm surge due to turbine arrays for Katrina and a 12% (21%) reduction for Sandy. Ref. 27 indicates that, above 2 m depth, a 100% increase in water depth increases storm surge damage (thus, damage cost) by ~132%, which is the ratio applied here. Average 15-m wind speeds within and downwind of turbines for both Katrina and Sandy were less than 45 m s^{-1}. Ref. 28 indicates that, below 45 m s^{-1}, 80–100% of wind speed damage is avoided, the range assumed here. §Levelized cost of electricity for new projects[29] (accounting for capital, fixed operation and maintenance, variable operation and maintenance (fuel), and transmission costs) weighted by present fuel mix[30] (coal, gas, oil, nuclear, biomass, geothermal, hydro, wind, solar) in Louisiana (for Katrina) and Maryland, Delaware, New Jersey and New York (for Sandy).

with greater storm surge reduction per added turbine at lower installed density.

As a sensitivity test, the modelled cutout wind speed of the 7.58 MW turbine was increased from this turbine's designed cutout speed (34 m s^{-1}; Simulation C) to the maximum certified wind speed (50 m s^{-1}; Simulation A). This increased the peak power extraction by ~11% and decreased storm surge by ~4% beyond that with the designed cutout wind speed (Table 1 and Supplementary Table 1). This suggests two conclusions. First, turbine arrays dampened most winds below 34 m s^{-1}, keeping winds within turbine-designed cutout speeds. Second, significant reductions in both wind speed and storm surge were obtained without increasing the turbine's designed cutout speed. Thus, even present-design turbines may be used to reduce hurricane intensity.

Table 2 shows a simple cost–benefit analysis on a per kilowatt-hour (kWh) basis, for wind turbines offshore of New Orleans and the East Coast, accounting for avoided hurricane, health and climate damage. The avoided hurricane damage (Table 2, footnotes) was 0.21–0.68¢ kWh^{-1} for New Orleans and 0.09–0.13¢ kWh^{-1} for the East Coast. The greater benefit to New Orleans occurred because it experiences more frequent hurricanes, and the arrays were placed only to the southeast of the city rather than along a long coastline; thus, fewer turbines were needed to reduce a similar level of damage. Turbines also reduce 2010 air pollution health and climate costs by ~5.3¢ kWh^{-1} by displacing fossil emissions.

The estimated direct cost of offshore wind energy for a large future build such as that proposed here would not be the 19¢ kWh^{-1} historical average cost of offshore wind. A better estimate is the 'best recent project cost' for better managed projects with winds such as those off New York, but in a still-immature industry of ~9.4¢ kWh^{-1} (ref. 11). Costs of integrating wind onto the grid are minimized when wind and solar, which are complementary in production times, are combined on the grid, and stored energy in the form of hydroelectricity and hydrogen and vehicle-stored electricity are used to fill in gaps in supply. In addition, using demand–response management; forecasting wind and solar resources; and using excess wind for district heat or hydrogen production rather than for curtailing, facilitates matching demand with supply[12–14].

Including hurricane damage avoidance, reduced pollution, health, and climate costs, but not including tax credits or subsidies, gives the net cost of offshore wind as ~4–8.5¢ kWh^{-1}, which compares with ~10¢ kWh^{-1} for new fossil fuel generation. The health and climate benefits significantly reduce wind's net cost, and hurricane protection adds a smaller benefit (~10% for New Orleans), but at no additional cost. In sum, large arrays of offshore wind turbines seem to diminish hurricane risk cost-effectively while reducing air pollution and global warming and providing energy supply at a lower net cost than conventional fuels.

Finally, what are the costs of sea walls versus offshore wind turbine arrays? Turbines pay for themselves from the sale of electricity they produce and other non-market benefits (Table 2), but sea walls have no other function than to reduce storm surge (they do not even reduce damaging hurricane wind speeds), so society bears their full cost. Conversely, if wind turbines are used only for hurricane damage avoidance, an array covering 32 km of linear coastline in front of New York City would cost ~$210 billion with no payback (Supplementary Information), higher than the cost of proposed sea walls, $10–29 billion[7]. Thus, turbines cost much less than sea walls to protect a city, as turbines also generate electricity year-round, but if turbines were used only for hurricane protection, sea walls would be less expensive.

Methods

Two regions are examined, the US Gulf and East coasts. Both have year-round offshore wind resources suitable for electricity generation[15–19] and both experience hurricanes[10,19]. Global-through-high-resolution-local simulations, described in the Supplementary Information, were run for hurricanes Katrina, Sandy and Isaac, without and with turbines. Two turbines (the geared RE Power 5 MW, with rotor diameter (D) of 126 m and designed cutout wind speed (c-o) of 30 m s^{-1} and the gearless Enercon E–126 7.58 MW, $D = 127$ m, c-o $= 34$ m s^{-1}) were tested with several variants (Table 1). In all cases, turbines were placed within 100 km of the coast, where the water depth is mostly <30 m but up to 50 m in some areas and 200 m in others (Supplementary Fig. 5).

The speeds at which the turbines are designed to shut down to minimize damage (the cutout wind speed) are 30–34 m s^{-1}. They are designed to survive a 10-minute sustained wind (maximum certified wind speed) of 50 m s^{-1} (ref. 20) when shut down. Here, two cases are tested: allowing turbines to generate power up to 50 m s^{-1} to further reduce wind speed at the risk of turbine damage; and running the turbines only up to 30–34 m s^{-1}. If only the first case worked, today's turbines would need substantial strengthening to reduce storm damage. Results indicate that the second case significantly reduced damage; thus, current turbine designs may suffice to dampen hurricanes when large arrays of turbines are used.

Received 23 September 2013; accepted 03 January 2014;

References

1. Pielke Jr, R. A. *et al.* Normalized hurricane damage in the United States 1900–2005. *Nat. Hazards Rev.* **9,** 29–42 (2008).
2. Knutson, T. R. *et al.* Tropical cyclones and climate change. *Nature Geosci.* **3,** 157–163 (2010).
3. Jacobson, M. Z. & Archer, C. L. Saturation wind power potential and its implications for wind energy. *Proc. Natl. Acad. Sci.* **109,** 15,679–15,684 (2012).
4. Jacobson, M. Z. GATOR-GCMM: a global through urban scale air pollution and weather forecast model. 1. Model design and treatment of subgrid soil, vegetation, roads, rooftops, water, sea ice, and snow. *J. Geophys. Res.* **106,** 5385–5402 (2001).

5. Lin, N., Emanuel, K., Oppenheimer, M. & Vanmarcke, E. Physically based assessment of hurricane surge threat under climate change. *Nature Clim. Change* **2,** 462–467 (2012).
6. Palmer, D. & Lawder, D. Sandy aid bill: Senate approves $60.4 billion hurricane recovery package. *Huffington Post* (*from Reuters*) (accessed 28 December 2012); http://www.huffingtonpost.com/2012/12/28/sandy-aid-bill-senate2378457.html.
7. Navarro, M. Weighing sea barriers as protection for New York. *New York Times* p. A21 (8 November 2012).
8. Klima, K., Lin, N., Emanuel, K., Morgan, M. G. & Grossman, I. Hurricane modification and adaptation in Miami-Dade County, Florida. *Environ. Sci. Technol.* **45,** 636–642 (2012).
9. Fischetti, M. Sandy versus Katrina, and Irene: Monster hurricanes by the numbers. *Scientific American* (November 2012).
10. McAdie, C. J., Landsea, C. W., Neumann, C. J., David, J. E. & Blake, E. S. *Tropical cyclones of the North Atlantic Ocean 1851–2006*. Technical Report HCS 6-2, National Oceanic and Atmospheric Administration. http://www.nhc.noaa.gov/pdf/TC_Book_Atl1851-2006_lowres.pdf (accessed 4 August 2013).
11. Levitt, A. C., Kempton, W., Smith, A. P., Musial, W. & Firestone, J. Pricing offshore wind power. *Energy Policy* **39,** 6408–6421 (2011).
12. Delucchi, M. A. & Jacobson, M. Z. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy* **39,** 1170–1190 (2011).
13. Budischak, C. *et al.* Cost-minimized combinations of wind power, solar power, and electrochemical storage, powering the grid up to 99.9% of the time. *J. Power Sourc.* **225,** 60–74 (2013).
14. Jacobson, M. Z. *et al.* Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. *Energy Policy* **57,** 585–601 (2013).
15. Archer, C. L. & Jacobson, M. Z. Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements. *J. Geophys. Res.* **108 (D9),** 4289 (2003).
16. Archer, C. L. & Jacobson, M. Z. Evaluation of global wind power. *J. Geophys. Res.* **110,** D12110 (2005).
17. Schwartz, M., Heimiller, D., Haymes, S. & Musial, W. *Technical Report NREL/TP-500-45889*. http://www.nrel.gov/docs/fy10osti/45889.pdf (accessed 29 November 2012).
18. Dvorak, M. J., Stoutenburg, E. D., Archer, C. L., Kempton, W. & Jacobson, M. Z. Where is the ideal location for a U.S. East Coast offshore grid. *Geophys. Res. Lett.* **39,** L06804 (2012).
19. Dvorak, M. J., Corcoran, B. A., Ten Hoeve, J. E., McIntyre, N. J. & Jacobson, M. Z. U.S. East Coast offshore wind energy resources and their relationship to peak-time electricity demand. *Wind Energy* http://dx.doi.org/10.1002/we.1524 (2012).
20. International Electrotechnical Commission, International Standard IEC 61400-3. August 2005.
21. Central Florida Hurricane Center. Google maps of storms Katrina and Sandy. http://flhurricane.com/googlemap.php?2005s12, http://flhurricane.com/googlemap.php?2012s18 (accessed 1 December 2012).
22. Knabb, R. D., Rhome, J. R. & Brown, D. P. Tropical cyclone report: Hurricane Katrina, National Hurricane Center. http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf (accessed 29 August 2013).
23. Blake, E. S., Kimberlain, T. B., Berg, R. J., Cangialosi, J. P. & Beven II, J. L. Tropical cyclone report: Hurricane Sandy, National Hurricane Center. 2013. http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf (accessed 29 August 2013).
24. Berg, R. Tropical cyclone report: Hurricane Isaac, National Hurricane Center. 2013. http://www.nhc.noaa.gov/data/tcr/AL092012_Isaac.pdf (accessed 25 November 2013).
25. Bender, M. A., Ginis, I., Tuleya, R., Thomas, B. & Marchok, T. The operational GFDL coupled hurricane–ocean prediction system and a summary of its performance. *Mon. Wea. Rev.* **135,** 3965–3989 (2007).
26. Tallapragada, V. *et al.* Hurricane Weather Research and Forecasting (HWRF) Model: 2013 Scientific Documentation. 99. 2013. http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRFv3.5a_ScientificDoc.pdf (accessed 27 November 2013).
27. Jonkman, S. N., Bockarjov, M., Kok, M. & Bernardini, P. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. *Ecol. Econom.* **66,** 77–90 (2008).
28. Unanwa, C. O., McDonald, J. R., Mehta, K. C. & Smith, D. A. The development of wind damage bands for buildings. *J. Wind Eng. Industrial Aerodyn.* **84,** 119–149 (2000).
29. EIA (Energy Information Administration). http://www.eia.gov/forecasts/aeo/electricity_generation.cfm (accessed 10 October 2012).
30. EIA (Energy Information Administration). http://www.eia.gov/electricity/data/state/ (accessed 31 December 2012).

Acknowledgements

We thank T. Marchok from NOAA/GFDL for helping compare results with operational model results. Funding sources include NSF, NASA and NASA high-end computing.

Author contributions

M.Z.J. developed the idea for the study and the GATOR–GCMOM atmospheric–ocean model and the treatment of wind turbine power extraction within it. He ran the simulations with the code and provided numerical output. C.L.A. coded and performed the storm surge analysis with output from the atmospheric–ocean model, developed figures, and performed the model validation analysis. W.K. performed the analysis of turbine strength and contributed to the economic analysis. All three contributed to writing and editing the article.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints.

Competing financial interests

The authors declare no competing financial interests.