Blown away: the physical facts of hurricanes Harvey and Irma

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Philip's article aims to provide key background knowledge of the physical geography essential for appreciating the impact of hurricanes such as Harvey and Irma.

Figure 1: Satellite image of hurricanes Katia, Irma and Jose (from left to right). **Photo:** ©NOAA

Accompanying online materials

The 2017 North Atlantic hurricane season earned its place in the record books. For the first time two category 4 storms hit the US mainland; Harvey made landfall in Texas and Irma in Florida. While Harvey broke US rainfall records, Irma achieved sustained wind-speeds of 298 kph (185 mph) over open water for the longer than ever recorded, leaving the US and many Caribbean islands to pick up the pieces.

Harvey and Irma, like many other North Atlantic storms, began off the western coast of Africa as convective thunderstorms, characterised by rising air which coalesced to create a low-pressure centre, drawing in air from the surrounding area, producing strong surface winds and forming a tropical depression. The conditions required to generate such proto-hurricanes are relatively well understood:

- sea temperature needs to be at least 26.5˚C
- the vertical temperature profile of the atmosphere needs to cool enough with height to enable convective thunderstorms to form
- there needs to be humid air in the troposphere
- there needs to be low wind shear (both horizontal and vertical) with height
- the storm needs to be at least 550 km from the Equator so that the Coriolis force can establish cyclonic rotation (which is why you don't find cyclonic weather systems within 5 degrees of the Equator).

Once formed, a tropical depression evolves into a hurricane as water evaporates from the ocean, transferring latent heat (the energy from insolation needed to change water's state from a liquid into a gas) into the atmosphere. 'Air parcels' (large bodies of the atmosphere with similar characteristics) spiral inwards towards the centre of the growing depression and convection within these creates bands of rain that spiral with the cyclonic rotation of the system. Where the air parcels meet near the centre, they form a wall of rising, water vapour-laden air which cools and condenses with altitude, releasing latent heat, and encouraging further convection until reaching the tropopause. The air now spirals outwards, before cooling sufficiently to sink back towards the lower troposphere and create the hurricane's secondary circulation.

The Coriolis effect deflects the flow of air because of the rotation of the earth. The deflection is to the right in the Northern hemisphere and to the left in the Southern hemisphere. In a hurricane air moves to the low-pressure centre, is deflected towards the right, and starts an anti-clockwise rotation. The outflow of air at the tropopause is deflected to the right and creates a clockwise rotation.

A hurricane converts heat energy into mechanical energy, and it will continue to grow while air parcels provide more heat energy than is lost. While warm air rises faster than it is being replaced at sea level, the central pressure in the developing hurricane will fall and the hurricane will intensify. Faster winds can deliver more air to the centre creating a positive feedback effect that persists until conditions change and the storm starts to dissipate.

The path of the hurricane – its propagation – is largely determined by the surrounding wind pattern within which it has formed and it is also influenced by nearby high- and low-pressure systems and latitude. As a hurricane propagates towards a coastline its characteristics vary across four quadrants relative to its direction of travel.

The effects of a hurricane vary spatially and it is essential to predict propagation accurately both to anticipate the physical impacts, and to minimise those impacts on people (information about the modelling of the weather accompanies this article online).

Physical impacts

Wind

When the kinetic energy of a high velocity wind is stopped by a surface it is transformed into a pressure which exerts a significant force. This, in addition to turbulence and complex eddies that form around obstacles can overwhelm a built structure, causing it to disintegrate. For example, a house with a surface area of 100m^2 facing directly into the path of a category 4 wind exerts a force equivalent to a weight of around 20.7 tonnes upwards (Figure 2).

Storm surge

A storm surge has two components: a **pressure surge** beneath the eye of the hurricane where the low atmospheric pressures cause the ocean to bulge upwards, and a much larger **wind-driven surge**, where, as the hurricane reaches the shallower water of the coast, the vertical circulation of water that creates waves is forced upwards creating a wall of water.

The severity of a storm surge is dependent on the geographical configuration of the location:

- the central pressure of the hurricane – lower pressure creates a high-pressure surge
- the size of the storm – bigger storms have stronger winds and affect an area for a longer period of time
- propagation speed – a higher surge is caused by faster storms on open coastlines and slower storms in bays and sounds
- angle of approach – typically the more oblique the angle, the lower the surge
- shape of coastline – a surge is higher on concave coastlines
- characteristics of the ocean floor – wide, gently sloping coastal shelves exacerbate a surge
- local features such as barrier islands, inlets, rivers, etc.

The total water level associated with a storm is a combination of tides, waves and freshwater input from precipitation. The effects of a storm surge can reach far inland: in 2008 the surge for category 3 Hurricane Ike travelled up to 55km inland.

Precipitation / flooding

A hurricane, by its nature, contains a lot of water. The degree to which this causes flooding is related to its speed, size and the nature of the land on which it falls (e.g. permeable, urbanised, well-drained, saturated, etc). Near the coast the impact of a storm surge will be heightened by freshwater flooding.

The causes of mortality due to tropical cyclones and hurricanes are dominated by the effects of water. These include risk of drowning, the impact of debris floating in floodwater, power lines downed by winds, and the outbreak of disease caused by stagnant water. A loss of basic services, such as water and electricity, can also increase the risk of death. At a retirement home in Florida a number of elderly residents died from heat-related illness because there was no air conditioning.

Mitigating the impacts includes a mix of infrastructure (such as drainage and hardening), land-use zoning, defences, and building regulations to promote storm-proof structures. Geospatial technologies allow a more detailed assessment of both the potential impacts and how to manage them down to street-level. It is also important to make sure people have information, by using radio and TV, social networks, and specific apps on the internet.

Harvey and Irma

Hurricane Harvey

Harvey made landfall near Rockport in Texas late morning on 25 August as a category 4 hurricane with sustained wind speeds of at least 210 kph. Normally a hurricane would dissipate and lose energy as it progresses inland but Harvey remained virtually stationary above Houston because its path was blocked by two high-pressure systems sitting in the south-eastern and south-western USA. In this position, it was able to draw water vapour from a particularly warm patch of ocean surface in the Gulf of Mexico, sustaining its energy and producing exceptional amounts of precipitation due to positive feedback by pulling warm moisture back up into itself and dumping it again as rainfall, producing exceptional amounts of precipitation, particularly in the north-east quadrant. Up to 131.8cm (52 inches) of rain fell on Houston over a period of 5 days, in addition to significant coastal flooding caused by storm surge (Figure 3).

Existing flood defences were overwhelmed, as were emergency services and the local population's capaability to mitigate the impacts.

Figure 2: Calculated force exerted by different wind speeds on a building of surface area of 100m^2 facing directly into the path of the wind.

Description (Beaufort rating)	Speed (kph)	Speed (m s^{-1})	Force (N)	Equivalent weight (approx.) (tonnes)
Light breeze (2)	8	2.2	290	0.029 (29kg)
Moderate gale (7)	56	15.7	14,789	1.5
Storm (10)	96	26.8	43,094	4.4
Hurricane (cat 4)	209	58.1	202,537	20.7
Hurricane (cat 5)	300	82.7	410,357	41.9

Seventy deaths were recorded, with several caused by electrocution and road traffic collisions. After three days Harvey moved back out onto the Gulf of Mexico before making landfall again just before dawn on 30 August in Louisiana, then proceeding inland and dissipating.

Although the hurricane's landfall was forecast several days in advance, its path was not predicted by the United States' key hurricane forecast models (see the accompanying downloads for this article), and the level of precipitation in Texas was unexpected. A more accurate prediction was made by the European climate model (ECMWF), which uses a significantly faster supercomputer iterating the model numerous times from slightly different starting conditions to create a better consensus forecast. A 2017 upgrade to the US model actually degraded the accuracy of forecasts, but there are plans to improve accuracy using data from the new satellite constellation CYGNSS.

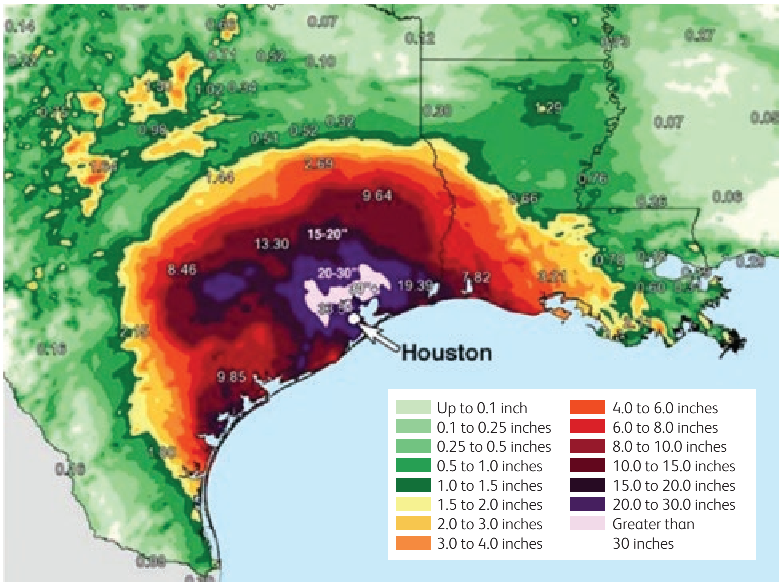

Figure 3: Precipitation amounts in Houston to 07:00 28 August, 2017. Please note that imperial units have been used here to remain true to the source of the map. **Source:** https://weather.com/safety/hurricane/news/hurricanes-tropical-storms-us-deaths-surge-flooding

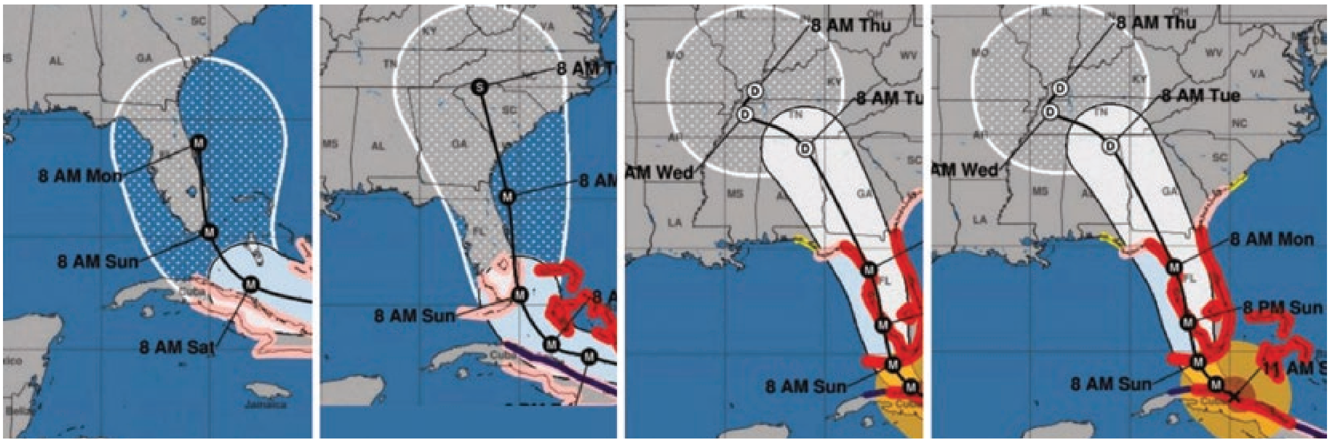

Figure 4: The progression of Irma's projected path (left to right) 11:00 6-9 September, 2017. **Source:** http://www.nhc.noaa.gov/archive/2017/IRMA_graphics.php?product=5day_cone_with_line_and_wind

Hurricane Irma

Hurricane Irma passed directly over Barbuda and severely impacted several other Caribbean islands before making landfall in Florida. This was well forecast several days in advance. Those living on islands were hit with the full force of a category 4/5 hurricane and there was significant damage. Irma set a new record for the highest, and most persistent wind speed of 300kph in an Atlantic hurricane – enough force to blow away an adult human.

The response to Irma, particularly on the US mainland, was once again complicated by uncertainty in forecast models. Although the European model indicated the actual path of the hurricane sooner, all models were late in showing a movement westwards across Florida (Figure 4). This made preparedness, evacuation and response in the short term more complex, given that several million people were affected. Logistics – supplying food, fuel, water, co-ordinating advice and support – were critical to minimising loss of life and damage to property. Uncertainty increases the economic cost, which initial estimates place at $300bn.

Climate change – connection or coincidence?

The rapid succession of four intense hurricanes in the Caribbean and Gulf region during late summer 2017 prompted suggestions they were caused by climate change. Hurricanes are complex phenomena and whilst global records indicate a linear upwards trend in frequency of tropical storms and hurricanes, the averages of storm incidence show significant variability over many years (see accompanying downloads). This 'noisy' pattern of averages makes it difficult to attribute the formation of particular hurricanes as an effect of climate change. However, first principles would suggest that as global sea temperatures rise there will be a greater supply of heat in the oceans with which to drive hurricanes. The 2017 sea surface temperatures in the Gulf of Mexico were warmer than normal, which probably helped fuel hurricanes Harvey and Irma, but there can be no certainty as to whether this increase was induced by climate change or simply a coincidental event. | **TG**

Further reading

A full list of websites and other sources of information on hurricanes is available to download from www.geography.org.uk.

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