

# MAS8306

## Topics in Statistics: Environmental Extremes



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# 1

## Background and motivation

### 1.1 Introduction

Finally, there is almost<sup>1</sup> a global consensus amongst scientists that our planet's climate is changing. Evidence for climatic change has been collected from a variety of sources, some of which can be used to reconstruct the earth's changing climates over tens of thousands of years. Reasonably complete global records of the earth's surface temperature since the early 1800's indicate a positive trend in the average annual temperature, and maximum annual temperature, most noticeable at the earth's poles.

Glaciers are considered amongst the most sensitive indicators of climate change. As the earth warms, glaciers retreat and ice sheets melt, which – over the last 30 years or so – has resulted in a gradual increase in sea and ocean levels. Apart from the consequences on ocean ecosystems, rising sea levels pose a direct threat to low-lying inhabited areas of land. Less direct, but certainly noticeable in the last fifteen years or so, is the effect of rising sea levels on the earth's weather systems. A larger amount of warmer water in the Atlantic Ocean, for example, has certainly resulted in stronger, and more frequent,

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<sup>1</sup>Almost...



tropical storms and hurricanes; unless you've been living under a rock over the last few years, you would have noticed this in the media (e.g. Hurricane Katrina in 2005, Superstorm Sandy in 2012). Most recently, and as reported in the New York Times in January 2018, the 2017 hurricane season was "... hyperactive, deadly and extremely destructive, featuring seventeen names storms and ranking alongside 1936 as the fifth most active season since records began". Most notable, perhaps, was Hurricane Maria, which devastated the islands of Puerto Rico and Dominica. The same can be said over the Pacific Ocean, where low-lying areas of Bangladesh, India and Malaysia are more frequently than ever battered by tropical cyclones. Closer to home, we have seen an increase in flooding events in the U.K. over the last fifteen years, with 2012 being the second wettest year on record and December 2015 being the wettest month since records began (largely due to Storm Desmond).

The world's changing climate is also likely to give rise to an increase in the frequency of periods of intense heat and drought. Though some parts of the world are familiar with the effects of extreme heat, we are beginning to see an increase in severe hot spells in more temperate latitudes – for example, the 2003 European heatwave which resulted in thousands of deaths. In drier parts of the world, this has resulted in an increase in devastating forest fires, and in developing countries an increase in famine.

## 1.2 Examples

### 1.2.1 Hurricane Katrina: Late summer 2005

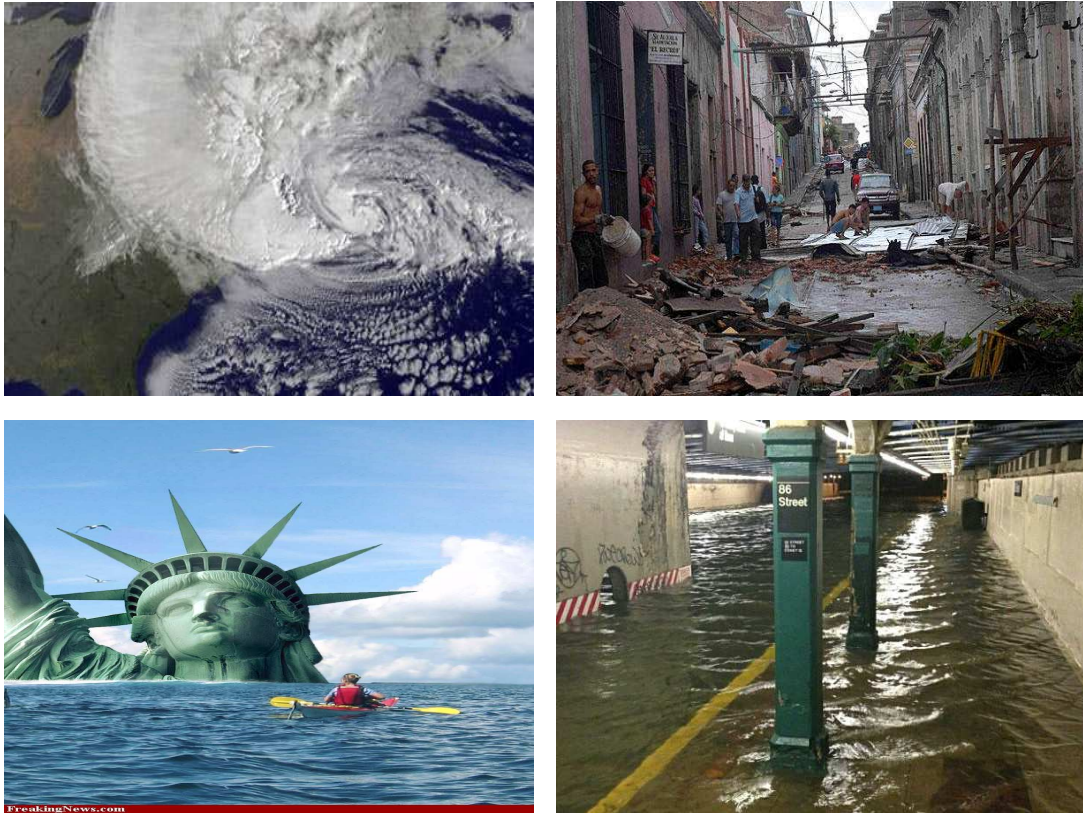
Hurricane Katrina made landfall as a category 3 hurricane (on the Saffir–Simpson hurricane scale, which goes from 1 (weakest) to 5 (strongest)) just south-west of New Orleans, on 31st August 2005. The tropical storm grew in intensity over the Atlantic ocean from mid-August, almost reaching hurricane category 5 status over the warm waters of the Gulf of Mexico at one point. Apart from wreaking havoc in Cuba and other Caribbean islands, the storm surge – the heightened levels of the sea as a result of extremely strong winds caused by record air pressure lows – over-topped the New Orleans flood defence systems ("levees" – see Figure 1.1) causing widespread flooding throughout the city and the surrounding area. There was a mandatory evacuation of the city, although many of the city's poorest people were left without transport and were trapped. It is estimated that the storm killed over 1,800 people (some are still unaccounted for), but displaced over a quarter of a million. Though still counting the cost, it is estimated that the storm caused over 100 billion dollars worth of damage. The highest one minute sustained wind speed recorded was 175mph, and the maximum recorded sea-surge at New Orleans reached nearly 14 feet (not verified).



**Figure 1.1:** Clockwise, from top-left: Satellite image of Hurricane Katrina as it approaches New Orleans; sea-surge breaching the London Street levee in the Lower Ninth Ward; flooded street after the hurricane had passed; my own photograph taken in the St. Bernard district five years later.

### 1.2.2 Superstorm Sandy: October 2012

Hurricane Sandy, billed in the media as a “superstorm” or “perfect storm” because of its level of organisation, devastated parts of the Caribbean and the mid-Atlantic and northeastern states of the USA. Sandy was the tenth hurricane of a busy hurricane season in 2012 (although not quite as busy as the 2017 hurricane season), and was a category 2 at its peak intensity. Causing an estimated 65.6 billion dollars worth of damage, this is the second costliest hurricane in US history, after Katrina, and 253 people were killed. The highest one minute sustained wind speed recorded was 110mph. Sandy’s strength and angle of approach combined to produce a record storm surge of water into New York City, with a maximum sea-surge of around 10 feet recorded just off Long Island. The path of Sandy was extremely unusual: after causing havoc in the Caribbean, Florida and the southeast United States, rather than racing out to sea like most coastal storms Sandy turned hard to the left and made landfall much further north than most hurricanes usually do. See Figure 1.2.



**Figure 1.2:** Clockwise, from top–left: Satellite image of Hurricane Sandy; downtown Havana, Cuba, three days after the storm; a flooded subway station one week after the storm; the next Sandy?

### 1.2.3 Extreme weather in the U.K.

The U.K. is no stranger to changing climate. The year 2012 was the second wettest year in the U.K. since records began, and six years since 1998 are in the top ten wettest years (1998, 1999, 2000, 2002, 2008 and 2012). December 2015 was the wettest single month on record. Flash-flooding in Glasgow in 2002 resulted in the evacuation of over 200 people from their homes, landslides, and the contamination of drinking water. Flooding in Boscastle (southwest England) in 2004 resulted in the destruction of over 100 homes and business properties; flooding across the entire UK in 2007, 2008, 2009 and 2012 – including severe flash-flooding in notoriously dry (!) Newcastle in June 2012 – resulted in a number of deaths, as well as millions of pounds worth of damage to properties and infrastructure. Observational studies and climate models indicate that the occurrence, and magnitude, of such extreme rainfall events will continue to increase in the future.

On a much more destructive scale was the “Great North Sea Flood” of 1953. On the night of 31st January a major European windstorm combined with a high spring tide



which resulted in a storm surge along the coasts of Holland, Belgium and Eastern Scotland/England of up to 18 feet. In total, 2,551 people were killed. The Great Storm of 1987, in which record-breaking hurricane-strength wind speeds battered parts of southeast England and northern France, killed 22 people – on a night in which the BBC weather forecaster, Michael Fish, infamously said: “Don’t worry, there won’t be a hurricane”! The “Burns Day Storm” on 25th January 1990 proved more deadly than the Great Storm of 1987, mainly because it hit during the day. It caused chaos, killing some children in their schools when the roof collapsed and throwing cars off the road. 47 people died and around half a million homes were left without electricity. However, unlike 1987, the UK Met Office had predicted the storm’s progress and had issued several warnings. Over the last decade or so the U.K. has seen a gradual shift in its wind climate, with gales, tropical storm-strength wind speeds and even tornadoes (e.g. Birmingham in 2005). See Figure 1.3.



**Figure 1.3:** Clockwise, from top-left: Effects of flooding in Cockermouth, Cumbria, 2008; Lightning strike of the Tyne Bridge during a flash-flood in July 2012; flooding in Zeeland, Holland, during the 1953 North Sea storm surge; the next big north sea storm surge?

### 1.2.4 Heatwaves and drought

The world's changing climate is also likely to give rise to an increase in the frequency of periods of intense heat and drought. Though some parts of the world are familiar with the effects of extreme heat, we are beginning to see an increase in severe hot spells in more temperate latitudes – for example, the 2003 European heatwave which resulted in tens of thousands of deaths (including around 2000 deaths in the U.K., mostly through heat stroke or dehydration). In drier parts of the world, this has resulted in an increase in devastating forest fires, and in developing countries an increase in famine.

Now – perhaps more than ever – the statistical analysis of the extremes of environmental data is in the spotlight. We need to get things right!

### 1.3 Why statistical modelling?

Statistical modelling of extreme weather has a very practical motivation: reliability — anything we build needs to have a good chance of surviving the weather/environment for the whole of its working life. This has obvious implications for civil engineers and planners. For example, in the context of some of the examples we have looked at so far, they need to know:

- How tall to build sea walls/flood defences – for example –
  - the levees surrounding New Orleans (Figure 1.1, top right);
  - flood defences in New York that were breached during Superstorm Sandy;
  - river and sea defences in the U.K.;
- How strong to make buildings – for example, in the U.K. the *British Standards Institute* specifies that new structures need to be strong enough to withstand the “Fifty year wind speed” ;
- How tall to build reservoir dams;
- How much fuel to stockpile;



This motivates the need to estimate what the:

- Highest tide;
- Heaviest rainfall;
- Strongest wind;
- most severe cold spell;

will be over some fixed period of future time. The only sensible way to do this is to use data on the variable of interest (wind, rain etc.) and fit an appropriate statistical model. The models themselves are motivated by asymptotic theory, and this will be our starting point in Chapter 2. Before this, let's start at a very basic level, and think about why we need statistical models at all.

## 1.4 Simple example: sea surges at Wassaw Island

Wassaw Island is a barrier island off the southeast coast of Georgia, in the USA. Any hurricanes about to make landfall on the mainland often hit such barrier islands first, substantially subduing the impending storm. Sea surge data is collected every hour; the data shown below are the extracted *annual maxima* for the years 1955–2004.

8.5	8.9	9.1	8.9	8.4	9.7	9.1	9.6	8.7	9.3
9.6	9.3	8.7	9.0	8.8	8.9	8.9	12.2	7.8	7.7
8.3	8.1	7.3	6.8	6.7	7.3	7.6	8.2	8.6	9.8
9.5	7.4	7.3	10.2	10.3	10.4	8.8	9.7	10.0	10.8
11.1	12.7	11.5	11.8	12.6	13.0	10.5	10.5	10.0	9.4

**Table 1.1:** Annual maximum sea-surges at Wassaw Island, 1955–2004 (inclusive). Units are feet.

1. Civil engineers are interested in various *exceedance probabilities*. For example, suppose they need to know the probability that sea-surge will exceed 8.75, 11.25 and 14 feet. Use the data to estimate these probabilities.



2. How high should state authorities build flood defences at the nearby city of Savannah if they want to protect the city against the sea-surge they would expect to see:

(i) Once every 10 years;

(ii) Once every hundred years?



### Further comments

