Hurricanes in the North Atlantic, should insurance pricing be based on long-term averages?

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Abstract

The key question this note attempts to discuss is **"do long-term average hurricane *landfall* rates adequately reflect current risk levels?"** In statistical parlance we could rephrase this as "is the hurricane landfall timeseries stationary?". It is important to realise the difference between genesis frequency (the number of storms actually arising each year) and US landfall frequency (note this excludes landfalling storms that fall outside of the US). Insurers are interested, primarily, in landfalling storms. This note will present a simple argument to suggest that we should assume the landfall series is not stationary; and should adjust long-term averages accordingly.

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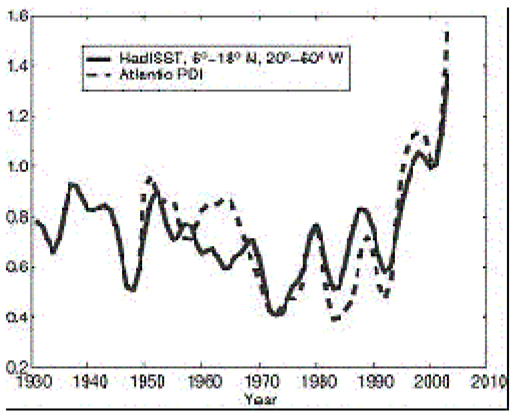
1 A short literature review

This section lists the views of some academics though it is well short of a full literature review.

1.1 Views on hurricane genesis probability

Professor Kerry Emanuel has created an index of Potential Destructiveness (PDI). In essence this is the cube of the wind speed, summed over the lifetime of the storm; and then summed over all storms in the season. So a storm that lasts for a long time will have a higher PDI; a powerful storm (with higher windspeeds) will have a higher PDI; and a season with lots of storms will, other things equal, have a higher PDI. Professor Emanuel shows that the seasonal PDI is strongly correlated with sea surface temperature, he also shows that it has risen considerably since the 1970s.

> "*…I define an index of the potential destructiveness of hurricanes based on the total dissipation of power, integrated over the lifetime of the cyclone, and show that this index has increased markedly since the mid-1970s.*
>
> *I find that the record of net hurricane power dissipation is highly correlated with tropical sea surface temperature, reflecting well-documented climate signals, including multi-decadal oscillations in the North Atlantic and North Pacific, and global warming. My results suggest that future warming may lead to an upward trend in tropical cyclone destructive potential, and—taking into account an increasing coastal population— a substantial increase in hurricane-related losses in the twenty-first century*"

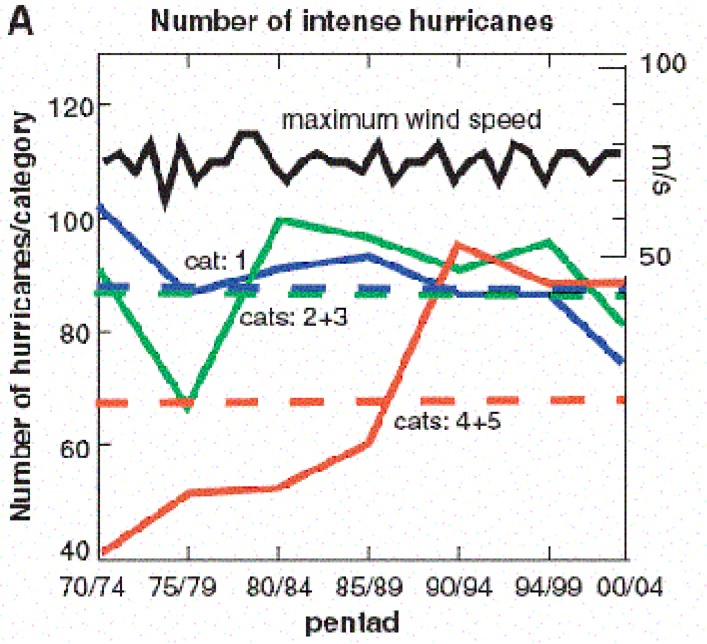


Emanuel, K.A. (2005) Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436, 686-688

Webster et al (2005) have analysed the frequency of storms of various strengths in all the major ocean basins around the world. They found that the number of larger storms has been increasing; offset by decreases in frequency of the smaller storms.

> "*We examined the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over the past 35 years, in an environment of increasing sea surface temperature. A large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurred in the North Pacific, Indian, and Southwest Pacific Oceans, and the smallest percentage increase occurred in the North Atlantic Ocean. These increases have taken place while the number of cyclones and cyclone days has decreased in all basins except the North Atlantic during the past decade.*"

Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment (2005) P. J. Webster,1 G. J. Holland,2 J. A. Curry,1 H.-R. Chang1



The quote below is from Jim Elsner et al concluding that conditioning on sea surface temperature, SST, (alone) gives prediction skill. The quote also contains a short summary of preceding academic work on the subject all concluding that hurricane *generation* frequency is not stationary.

> "*For a given forecast year, a predicted hurricane count is conditional on a sampled predicted value of Atlantic SST. Thus forecasts are samples of hurricane counts for each future year. Model skill is evaluated over the period (1997–2005) and compared against climatology, persistence, and other multiseasonal forecasts issued during this time period. Results indicate that the algorithm will likely improve on earlier efforts and perhaps carry enough skill to be useful in the long-term management of hurricane risk…*
>
> *…Statistical analysis confirms that over the Atlantic basin warmer SST tends to result in more and stronger hurricanes. Saunders and Harris (1997) using linear regression showed that SST over the tropical Atlantic is the dominating influence behind the interannual variance in Atlantic hurricane numbers. Kimberlain and Elsner (1998) showed that the increase in hurricane activity since 1995 could be related to warmer SSTs to the east of the Lesser Antilles. Goldenberg et al. (2001) show that the number and strength of Atlantic hurricanes have a multidecadal variation which they suggest is related to SST changes resulting from North Atlantic Ocean currents.*"

Improving multiseason forecasts of North Atlantic hurricane activity James B. Elsner, Thomas H. Jagger, Michael Dickinson, and Dail Rowe

Not all scientists agree with this. Landsea et al (2006) for example believe that much of the trends observed are due to changing practices of data collection over the years which may have led to an overstatement in recent times of intense hurricanes. Other scientists believe these effects will be small though.

There has been much disagreement about whether global warming is the cause of increased storm activity. It is crucial to realise that that is *not* the issue being discussed here. For example Roger Pielke has strongly argued against climate change being the cause of increased hurricane activity; but still we see the quote below which agrees that there has been a step change in hurricane genesis of late.

> "*Since 1995 there has been an increase in the number of storms, and in particular the number of major hurricanes (categories 3, 4, and 5) in the Atlantic.*"

Hurricanes and global warming by R Pielke JR., C. Landsea, Mayfield, Laver, Pasch

William Gray and Philip, J Kloztbach are well known for their annual hurricane forecasts; Gray in particular is vociferous against the theory that global warming is responsible for increased hurricane activity. But again they are clear that there has been an increase in genesis rates.

> *"The Atlantic has seen a very large increase in major hurricanes during the last 11-year period of 1995-2005 (average 4.0 per year) in comparison to the prior 25-year period of 1970-1994 (average 1.5 per year). This large increase in Atlantic major hurricanes is primarily a result of the multi-decadal increase in the Atlantic Ocean thermohaline circulation (THC) that is not directly related to global temperature increase. Changes in ocean salinity are believed to be the driving mechanism. These multi-decadal changes have also been termed the Atlantic Multi-Decadal Oscillation (AMO). There have been similar past periods (1940s-1950s) when the Atlantic was just as active as in recent years. For instance, when we compare Atlantic basin hurricane numbers of the last 15 years with an earlier 15-year period (1950-64) we see no difference in hurricane frequency or intensity even though the global surface temperatures were cooler and there was a general global cooling during 1950-64 as compared with global warming during 1990-2004"*

Summary of 2005 atlantic tropical cyclone activity and verification of author's seasonal and monthly forecasts. by William Gray and Philip Klotzbach

So, the above quotes show that there is broad agreement that there are trends in the number of hurricanes generated (the genesis frequency) in the North Atlantic, particularly for major storms. The next section looks at academic views on landfalling frequency.

1.2 Views on landfalling frequency

Dr Tim Hall from NASA and Dr Steve Jewson from RMS have been working together on a stochastic model of hurricanes. Their model broadly reproduces actual statistics and passes a number of credibility tests. They subdivide the time series into "warm years" and "cold years" according to the underlying sea surface temperatures. They find that the frequency of tropical cyclones (including hurricanes and weaker storms) is significantly higher in warm years. They also find that that there *are* predicted to be more storms making landfall.

> "*TC number has a large and well known dependency on SST: there are 45% more TCs in the hot years than cold, a difference which is highly significant compared to random sampling….Landfall rates on the Florida and northern U.S. Gulf Coasts are higher in hot years than cold,…. our results show a significant increase of North American TC landfall with tropical SST in rough proportion to the increase in TC number. The implication is clear for higher TC landfall risk with future SST increases.*"

SST and North American Tropical Cyclone Landfall: A Statistical Modeling Study Timothy M. Hall NASA Goddard Institute for Space Studies, New York, NY Stephen Jewson Risk Management Solutions, London, U.K.

Professor Elsner, Tom Jagger from the US and Dr Mark Saunders from the Benfield Hazard Research Centre have been looking into prediction methods. They find that various natural time series (sea surface temperatures, the North Atlantic Oscillation index and the El Nino Southern Oscillation index) are predictive of more extreme seasons. Given that these series are not stationary (with well known trends and oscillations) then it seems likely that hurricane generation frequency is not stationary either. They have also analysed the dependency of insured hurricane losses to the underlying natural drivers (SST, NAO, ENSO etc). They find that losses (and hence landfalling storms) can be predicted with some skill.

> "*we found that climate conditions prior to a hurricane season provide information about possible future insured hurricane losses.*"

Forecasting US insured hurricane losses THOMAS H. JAGGER, JAMES B. ELSNER, AND MARK A. SAUNDERS

1.3 Summary

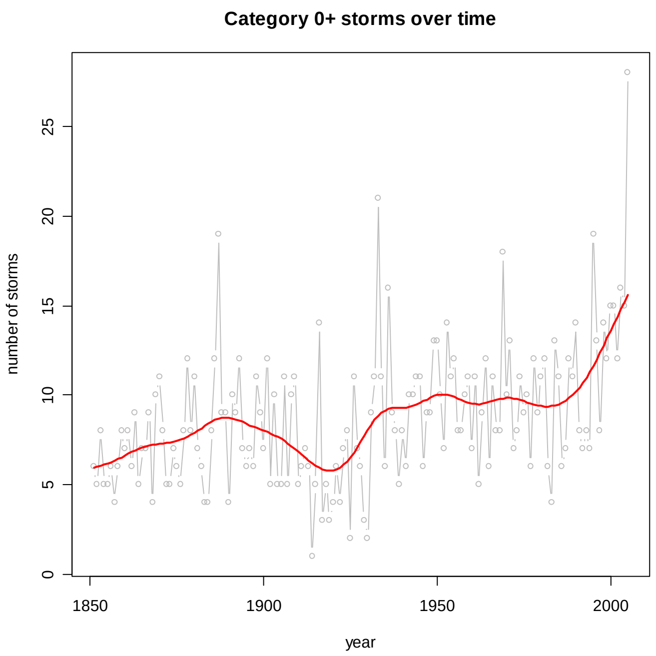
In summary, there is general agreement amongst climate scientists that, in the North Atlantic we are in a period of elevated hurricane *genesis* frequency. Some attribute this to global warming, some to the, so called, Atlantic Multidecadal Oscillation of sea surface temperatures. Many but not all of them are predicting more intense storms in future and some argue that, due to the greater numbers being generated, we will also see more making landfall.

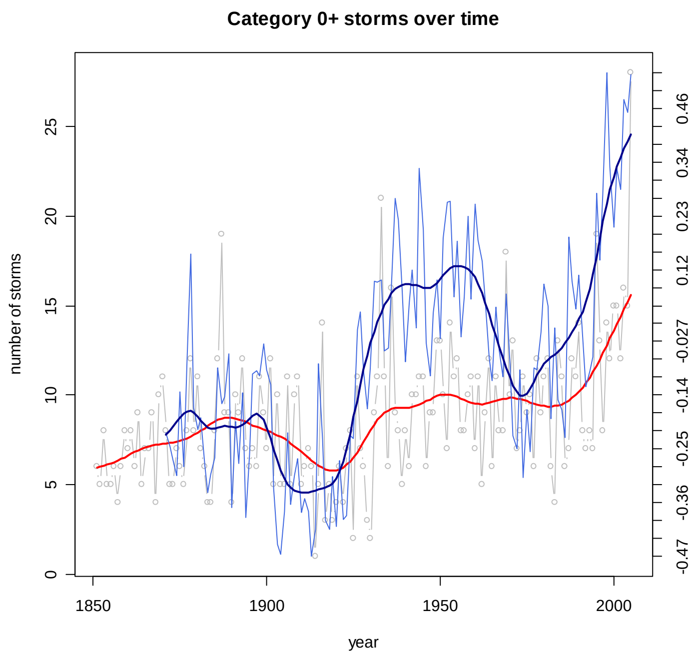
2. Some simple investigations

The following analysis uses the freely available HURDAT data set from NOAA.

2.1 All storms in North Atlantic

If we look at tropical storm numbers (whether or not they make landfall) since 1851 in the North Atlantic we see a strong average increase over time. We use the term “Category 0+” to include all tropical storms, including both tropical cyclones (category zero) and hurricanes (categories 1-5). The grey points are the yearly storm counts; the red line is a smoothed moving average[2], which illustrates the overall increasing trend. Clearly there is significant variability around this trend.





The second chart shows the sea surface temperature[3] superimposed (and on the right hand axis). Again the light blue line is actual data and the dark is a smoothed trend[4]. There is a degree of correlation between these two smoothed trends (as many scientists have already pointed out); both have an upward tilt; both show an approximate cycle and the peaks and troughs of these cycles approximately coincide. If we look at the correlation of the annual data rather than the smoothed averages we see less correlation (around 10%) which suggests the dependency is not straightforward.

We can expect the sea surface temperature trend to continue to increase over the next few years (though of course with natural fluctuations around this) and the dependency between temperature and number of hurricanes suggests we can expect more hurricanes than average in future. Both series are well above their historical average; both series are clearly non-stationary.

This is in agreement with the views of scientists in the previous section.

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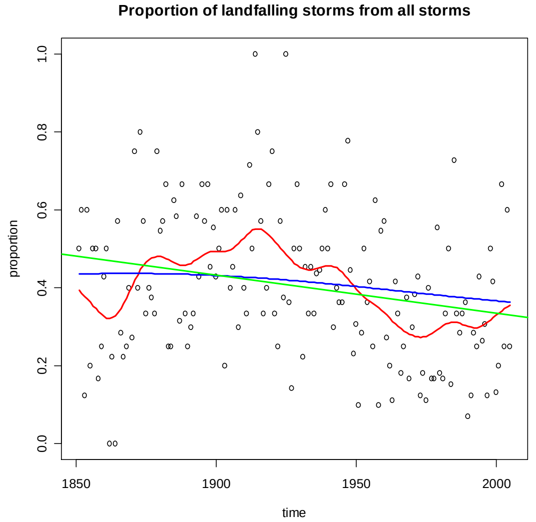
[2] In fact this is a Gaussian kernel smoother with a 15 year bandwidth

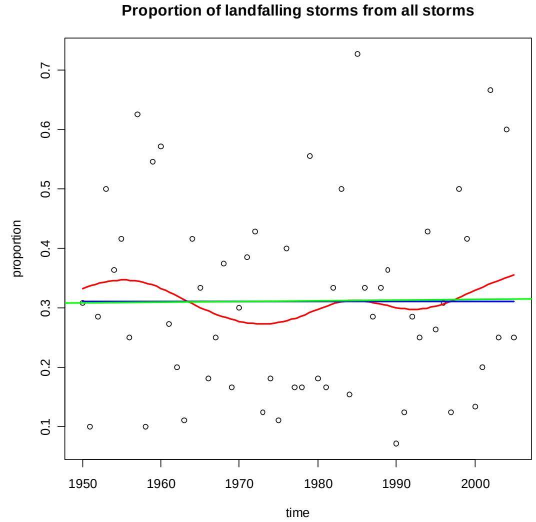
[3] Actually these are differences from the mean temperature, hence they vary around zero.

[4] This time a 10 year bandwidth.

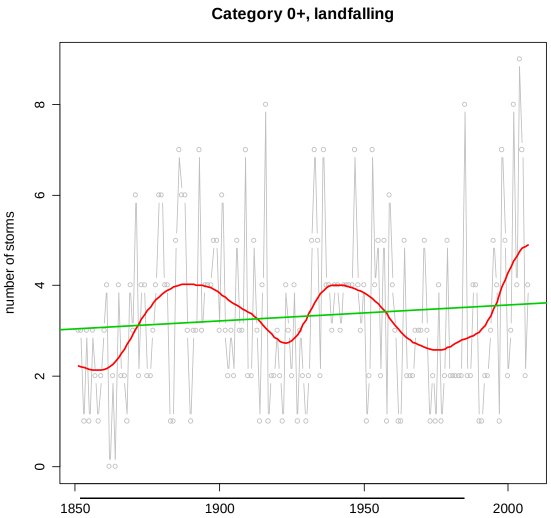
2.2 US landfalling storms

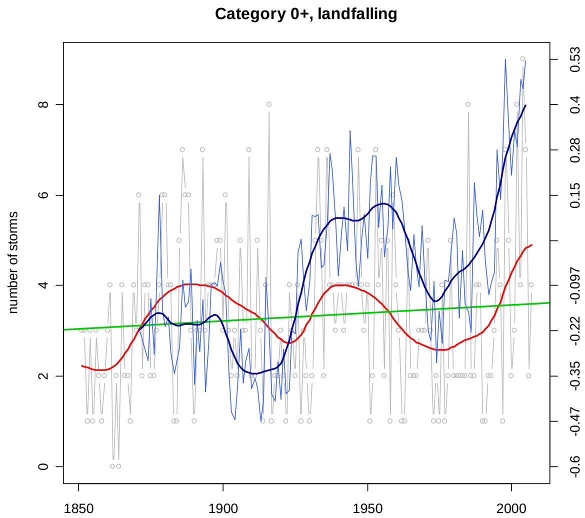
The proportion of landfalling storms (when compared to those generated) has remained broadly constant over time though there is a suggestion it is decreasing if we look at data from 1850[5]. Roger Pielke and Chris Landsea have noted that data quality prior to 1950 is less reliable, in particular that cyclones that didn't make landfall may have been missed in the past (because ships had to actually observe them) whereas landfalling storms tend to cause destruction and are not easily missed. The graphs below are consistent with this; prior to 1950 the proportion making landfall is higher; however, since the 1950s, when data is more solid, there is little trend in landfalling proportions. It seems reasonable that the proportion is higher because of missing non-landfalling storms in the dataset. The following paragraphs add weight to this.





Now if we look at US[6] *landfalling* storms frequency data we see again a trend of increasing numbers of storms since records began. A far more important point though is that the moving average cycles significantly above and below this trend over time; and at present is materially above both the trendline and also the long term average. **This series does not appear to be stationary.** When we add the AMO to the picture (blue line) we again see a correlation between large scale features (peaks and troughs etc).





[5] Red line is 15 year bandwidth smoother, blue line is a 150 year bandwidth and green is straight line fitted through the data.

[6] Note this excludes storms that make landfall but not in the US. So for example in 2007 it excludes the two category 5 storms that made landfall in Mexico.

We can do the same analysis but limiting ourselves to hurricanes of various strengths. These graphs are shown in appendix 1. In general terms the data appears non-stationary and broadly correlated with the AMO (though for categories 4+ and 5+ this is not clear). In most cases there is a small increasing trend over time (though for category 1+ the trend is negative), but none of these look significant. In *all* cases current average activity is above the trend and the long term average. **Again it seems clear that this data is not stationary.**

2.3 Is it right to draw conclusions from land falling time series alone?

The higher the storm category the more sparse the data; especially for landfalling storms. This section demonstrates that for a simple model of landfalling hurricanes there is a good chance of seeing a negative trend in the data; even if there is an underlying positive trend. Insurers are interested in the underlying trend.

There are other more statistically significant data sets which can infer information about landfalling Hurricanes (natural time series such as AMO, NAO, ENSO etc) and also storm genesis data (given that as shown in section 2.2, there are fairly constant relationships between the proportions that make landfall). It is important to use *all* the available information when calculating the current level of risk.

2.3.1 Model

A re-sampling approach is carried out as follows:

- Take the actual data for category 0+ storms as a base point. We are therefore *given* the number of landfalling storms in the year from empirical data. (Say this is M_i in year i)
- Assume that each landfalling storm in a given year had a probability of being a hurricane (of category N or above) and that this probability (p_N) is not changing over time. (Appendix 2 suggests this assumption is reasonable)
- Take the number of Category N storms as the number of Bernoulli trials in the experiment. Sample from a binomial distribution with the proportion becoming a hurricane of strength N as the success probability. This will generate pseudo hurricane data of the required category or above[7].

Then we can test how stable this pseudo data is and whether it is safe to draw conclusions from it.

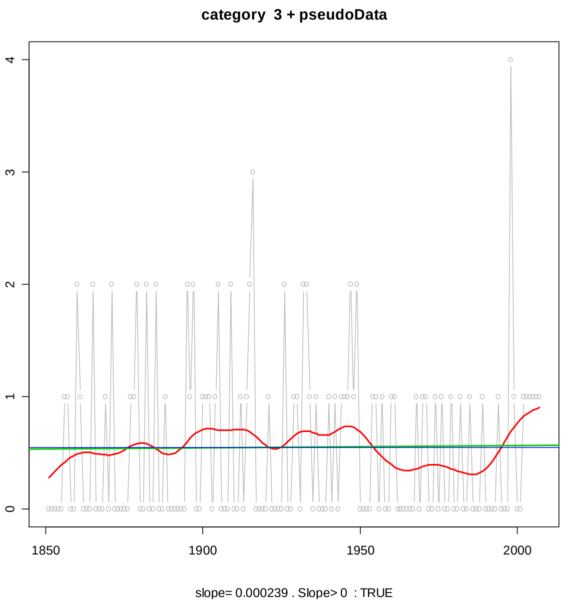
Based on real data we can calculate the average proportion (p_N from above) of landfalling storms that are hurricanes of various categories:

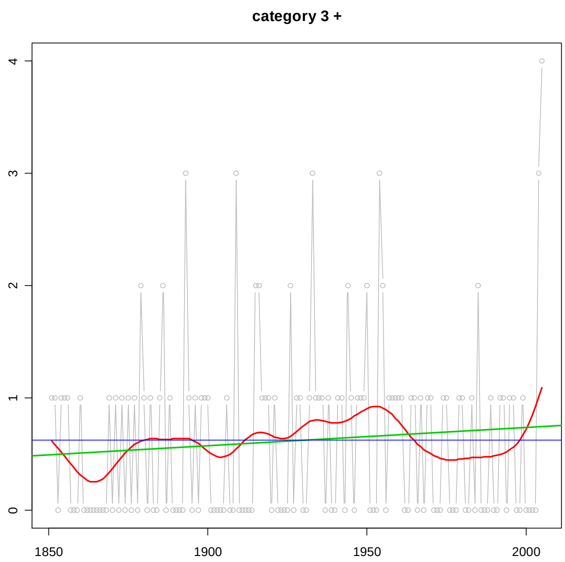
Category	Proportion of landfalling reaching (or exceeding) category
1	0.5302
2	0.3155
3	0.1799
4	0.0388
5	0.0096

There is reasonable evidence that these proportions are constant over time. See appendix2 which shows that whilst a linear fit to the individual ratios doesn't produce a horizontal straight line (which would be clear demonstration) the significance of any trend (and some are positive, some negative) is very low in all cases.

[7] So if we denote "pseudoN+" as pseudo category N or above data we have: pseudoN+ $\sim Bin(M_i, p_N)$

Based on these probabilities the graph on the left below shows some pseudo data for category 3+, the graph on the right is the actual category 3+ landfalling numbers for comparison.





2.3.3 Results

The pseudo data is generated from category 0+ landfalling numbers which we *know* has an underlying trend. We resample from this allowing for a certain proportion to be hurricanes; this proportion is constant across all years (in our experiment). So the underlying trend line is preserved on average; but any individual simulated set of pseudo data may or may not have the trend; due in particular to the sparcity of the data[8]. In the above (left hand picture) we see that the trend is (as it happens) preserved; though is weaker than the trend in the true data (right hand picture).

If we create many sets of pseudo data for each category we can see how many times the fitted (green) line is negative. This would be a clear error since we know (by construction of our model) that the underlying trend should be positive.

The table below shows the proportion of pseudo data that has a negative trend line (out of 1000 simulations) for each category:

Category	Proportion of psuedo data sets with negative slope
1	0.105
2	0.216
3	0.296
4	0.426
5	0.489

So for example for category 3, some 30% of the time the pseudo data shows a negative slope despite there being a genuine underlying positive trend. This suggests that use of land falling data alone is not very credible.

[8] Since pseudoN+ ~ Bin(M_i, p_N) we have E(psuedoN+)= M_i . p_N So as there is a trend in M_i there will be in the pseudo data too.

3 Conclusion

Scientists are clear that the genesis frequency of tropical cyclones has increased over time and particularly since 1995. The simple analysis in this paper agrees with their findings. This series is not stationary.

Many, but not all scientists, are of the view that the number of landfalls is a non-stationary time series. Some believe that other natural time series (AMO, NAO, ENSO) are reasonably skilled predictors of landfalling hurricane risk and even insurance losses. This additional data should be used to infer risk.

The simple analysis in this paper demonstrates a clear trend for genesis frequencies and we would argue also for landfalling tropical storms (of all sizes). The proportion of all storms that make landfall appears to be stable since the 1950s; hence an increasing trend in all storms would infer a trend in landfalling storms. We believe this is observed. The proportion of landfalling storms that are hurricanes is also relatively stable over time.

For landfalling hurricanes we believe that the data is too sparse to derive direct conclusions, particularly for those of the higher categories, and it is better to use other more credible data sets to infer risk levels.

For all the empirical data sets current (smoothed) levels of activity are above long term trends and long term means. This strongly suggests that none of these time series are stationary.

Based on this analysis we suggest that using long term averages in insurance modelling is not appropriate. A view which takes into account *current* levels of risk is both more accurate and more prudent (though the latter may not always be true).

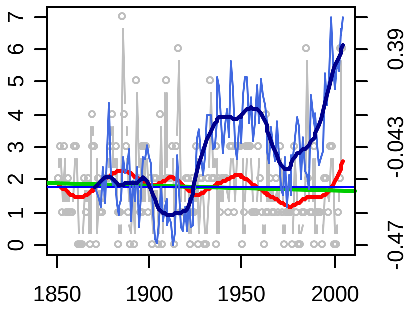
Appendices

Appendix 1 – US landfalls of various categories

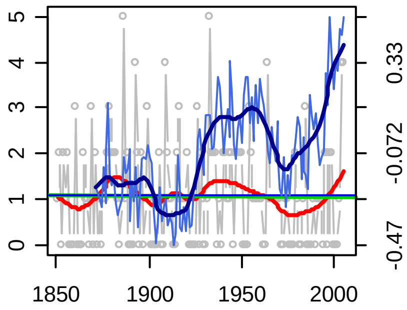
The graphs below show US landfall numbers over time (grey dots), the red line is smoother through this data; the blue (straight) line is the long term average of this data; the green line is a least squares straight line through the data. The light blue jagged line is the raw AMO data and the dark blue line is a smoother through this data.

Category 1+ means storms of category 1 ***or above*** (etc).

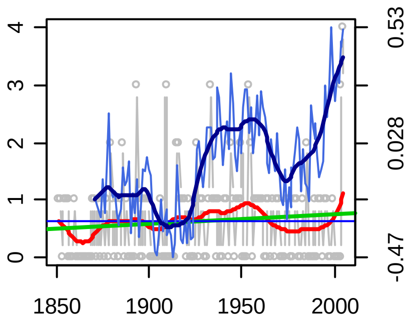
category 1 +



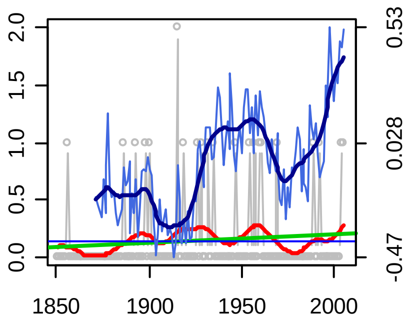
category 2 +



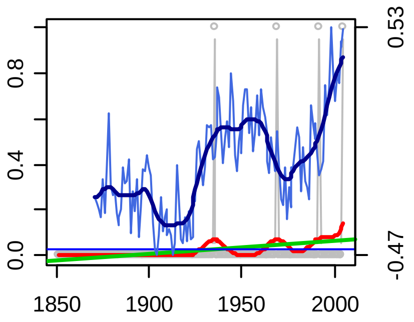
category 3 +



category 4 +



category 5 +



Appendix 2 – Ratio of landfalling hurricanes to all storms per year

For example if the number of landfalling storms of all categories is 10, and 3 of them are cat 1, and 1 of them is cat 3 then the ratio will be: 40% for cat 1+, 10% for cat2+, 10% for cat3+ and 0% for cat4+ and cat5+. The data shows that there is no (significant) trend in these ratios over time (the p value of all the trend lines is very low).