# LONG TERM VARIABILITY OF HURRICANE TRENDS AND A MONTE CARLO APPROACH TO DESIGN

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**Abstract**: An examination has been made of multi-decadal and longer-term trends in hurricane frequency and intensity in the North Atlantic and Caribbean Basins. The investigation points to an increasing occurrence of hurricanes, which may also be more intense. There appears to be a strong link between global warming impacts and these findings. This paper presents a recommended methodology for incorporating these anticipated changes into the development of a design wave climate for coastal infrastructure in the Caribbean.

## INTRODUCTION

Every year between the months of June and November, the Caribbean region becomes very vulnerable to tropical cyclones. Within this area, these storms are known as hurricanes, whereas in the Pacific Ocean region they are known as typhoons. Most hurricanes and tropical storms form approximately between the latitudes of 5°N and 25°N off the west coast of Africa, and then track across the Atlantic Ocean (Figure 1). Their effects can be devastating and often result in loss of life and significant damage to infrastructure.

A tropical cyclone is classified as a hurricane only after it has attained one-minute maximum sustained near-surface (10m) winds of 33m/s or more. Below this, these storms are referred to as Tropical Storms. Damage from hurricanes occurs primarily as a result of extreme winds, flooding, high waves and storm surge. An indication of fatalities between 1970 and 1998 is given in Figure 2, following. It must also be noted that these charts do not include the approximately 10,000 deaths that were recorded in Honduras as an indirect result of Hurricane Mitch in 1998 (fatalities occurred as a result of landslides).

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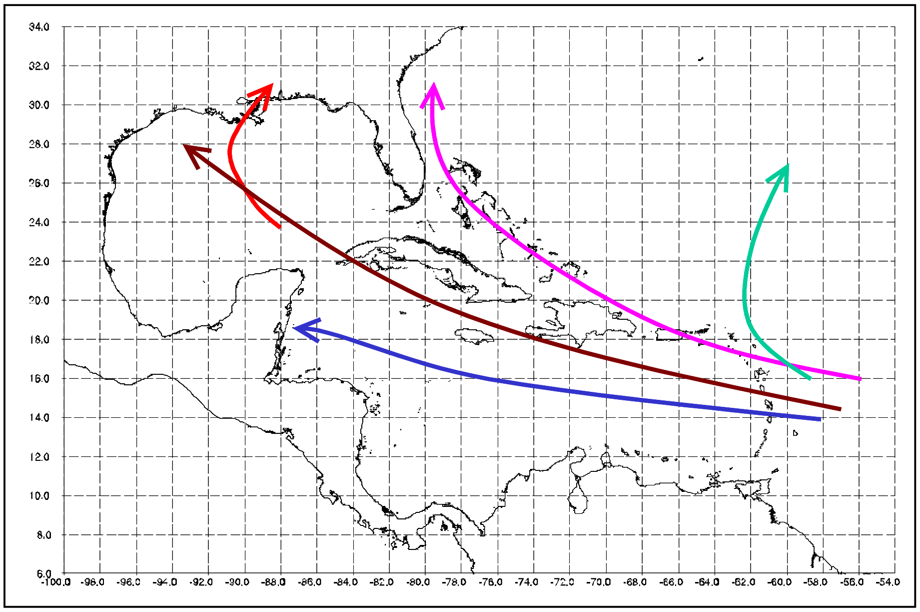


Figure 1. Typical hurricane tracks across the Atlantic Ocean

When one considers that the region is exposed to this natural threat every year, it is therefore of paramount importance that the hurricane phenomena be understood as completely as possible. Further, since the design of any coastal infrastructure in this environment will be governed by an assessment of hurricane waves, then the definition and use of appropriate statistical techniques is welcomed.

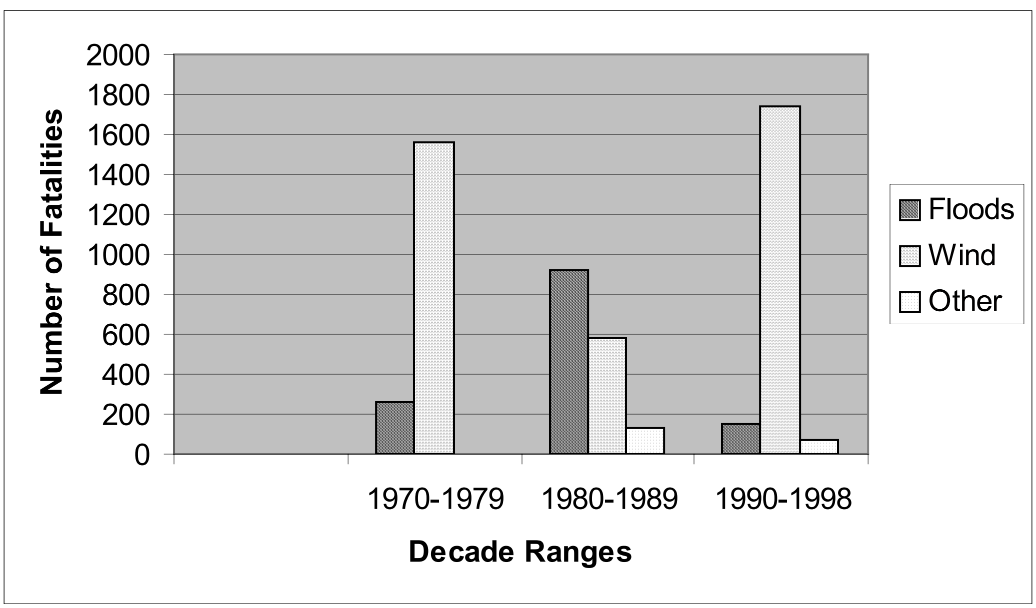



Figure 2. Fatalities in the Insular Caribbean and Belize by Type

In recent years, and particularly since 1995, the North Atlantic Basin (and by inclusion the Caribbean region) has seen an increase in the frequency and intensity of Tropical Cyclones. It has been proposed that this increase may be as a result of the global warming phenomena. To date, there is no conclusive evidence that these observed changes may be part of a cyclic climate trend, or indeed as a direct result of global warming.

What *is* known is that hurricane formation is influenced by sea surface temperature (SST) and vertical wind shear ($V_z$) between the upper and lower troposphere. A local SST greater than 26.5°C is usually considered necessary for the development of a tropical cyclone. Above this, there is a contribution to decreased atmospheric stability, which enhances the formation of a vortex. Strong values of $V_z$ inhibit the formation and/or intensification of tropical cyclones by preventing the organization of convection. Tropical cyclone formation is more favourable for $V_z$<~6m/s (Goldberg, Landsea et al. 2001).

Perhaps the most obvious indicator of climate change impacts on hurricane formation may be the number of hurricanes that occur within the Caribbean region. Figure 3, following, plots the number of occurrences of Tropical Storms and Hurricanes in the Atlantic Basin from 1900-2000. Over this period, there has been, on average, eight storms per year. The data is plotted for each year, either above or below the mean value.

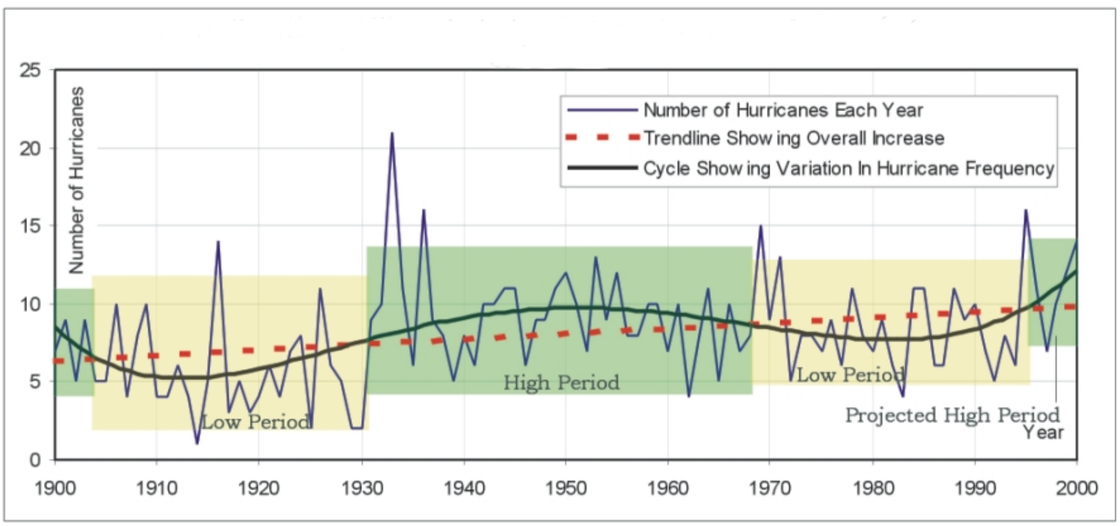



Figure 3 Number of occurrences of tropical storms and hurricanes in the Atlantic Basin from 1900-2000

These results clearly indicate a multidecadal trend, with the period from approximately 1930-1970 being one of increased hurricane activity. It should be noted that another period of increased activity commenced after 1990. A linear fit to the data shows that underlying this multidecadal (cyclical) trend, there is a slow rising trend. This underlying trend indicates that the average number of hurricanes per year is increasing by a rate of three to four hurricanes per 100 years (i.e. over a 100 year period, the mean will increase from 8 to 11 cyclones per year).

**Existing Approaches to Developing Design Criteria**

For the Coastal Engineer, the challenge is often in developing a design wave that corresponds to a particular return period. For most, if not all, coastal structures in the Caribbean, the hurricane (i.e. extreme) conditions dictate the structural design. Conversely, operational wave conditions dictate spatial (environmental) impacts.

The typical approach to derivation of hurricane waves is described following. These methods are summarized in Goda (1988).

- Use of a hindcast model to describe the waves in a storm. These models range from complex spectral to simpler parametric models. The spectral models give excellent predictions, but are computationally inefficient, therefore the number of storms that can be simulated is small. Parametric models, such as Cooper (1988) and Young (1988 and 1996) allow for the simulation of large numbers of storms.
- Selection of an appropriate data set. Typically, this could be:
  - ⇒ A peak value series, where only the peak wave height from each storm is used. The underlying assumption is that each point can be considered to be a random independent variable.
  - ⇒ An annual maximum series, whereby only the maximum wave height from all storm occurrences in a given year is used. One drawback to this method is that in an active year, near-maximum wave heights would be ignored. One such example occurred on the islands of Anguilla and St. Maarten in 1995, when two Category 4 hurricanes hit these islands (with damaging waves) within a one-month period.
  - ⇒ Both methods assume that future storms resemble past storms and that there are no meteorological trends in storm generation. As has been seen from the previous analysis, this latter assumption may be invalid.
- Fitting of the data set to a distribution. Typically used distributions include:
  - ⇒ Fisher Tippett type I or Gumbel Distribution
  - ⇒ Fisher Tippett type II or Frechet Distribution
  - ⇒ 3-Parameter Weibull Distribution
- Extraction of design waves for given return periods using any number of data fitting methods (e.g. graphical, least squares, moments, etc.).

Alternatively, a method of Monte Carlo simulations can be used. This method calls for the generation of a synthetic database using the properties of the existing historical population. Inherent assumptions for the validity of this method include the statistical independence of the main parameters. In general, the randomness associated with hurricane tracks and their peak velocities makes this method quite applicable to the development of design criteria.

Investigations carried out into the spatial distribution of peak velocities, $V_{max}$, (Banton, 2002) indicate that most occurrences of this peak value have been over the Atlantic Ocean, far away from the dampening effects of land. Interestingly, there is also a concentration of peak $V_{max}$ values offshore the coastline of the Gulf of Mexico. In summary, the investigations described above indicate that the peak $V_{max}$ may be a good parameter to use in a Monte Carlo simulation (along with track characteristics).

Analysis of temporal trends of peak $V_{max}$ were carried out for the North Atlantic Basin for the years 1900-2000. The results of this analysis are shown in Figure 4, following. This figure shows the annual variation of peak $V_{max}$ for the 100-year data set. The polynomial trend line indicates a multidecadal cycle, with a minimum value in approximately 1910-1914 and a maximum in approximately 1965-1969 (i.e. a half-cycle). Further, the trend shows that a minimum was reached in 1990 and that we are now in an ascending phase. Fitting a linear trend line to the data also indicated a definite increase in this parameter.

Further analysis of the 100-year database of peak $V_{max}$ was carried out. Specifically, the data was split into two 50-year periods (1900-1949 and 1950 – 2000 respectively), which approximately coincided with the half-period identified. Extraction of 25-year return period values from each of these data sets yielded significantly different results, indicating that they represent two different population sets.

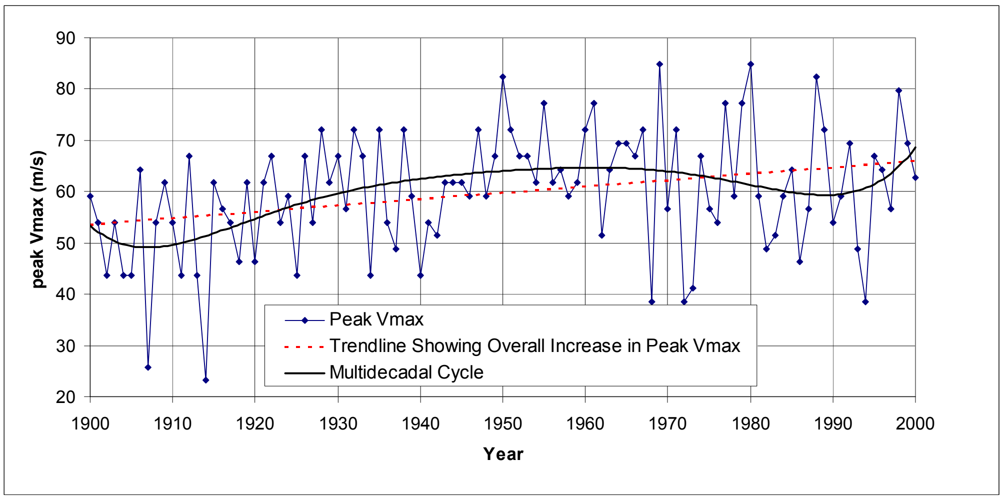



Figure 4 Temporal distribution of peak $V_{max}$ from 1900-2000

## Recommended Approach to Developing Design Criteria

Given the temporal variations observed in the hurricane database, a method for predicting design wave condition in the Caribbean region is proposed. This method is intended to incorporate the multidecadal cycles observed, as well as the long-term trends in the peak $V_{max}$ parameter. Essentially, a Monte Carlo simulation technique is used which operates within a purpose-developed computer programme, HURWave, which is capable of carrying out rapid hindcast analysis for hurricane waves. The program incorporates a number of parametric wind and wave models and statistical procedures.

Following is a summary of the method proposed:

1. Predict the increase in peak $V_{max}$ for the particular year of interest. For example, a structure designed in the year 2000 with an anticipated project life of 20 years would require an estimation of peak $V_{max}$ to the year 2020. A "half-cycle" approach was adopted since the peak $V_{max}$ parameter demonstrates distinct multi-decadal ascending and descending phases. The first ascending phase within the data occurs between approximately 1910 and 1955. The descending phase went from (approximately) 1955 to 1992. An observed second ascending phase is observed

from 1992 to the end of the data set. In order to predict a value of peak $V_{max}$ to the year 2020, the gradient from the first ascending phase was applied. This is shown in Figure 5. A formula was derived from this data which gives the projected peak $V_{max}$ in a given year:

$$pV_{max\_yr} = 0.26(yr-1900)+60$$

where $pV_{max\_yr}$ is the projected maximum wind speed in m/s in a given year (yr).

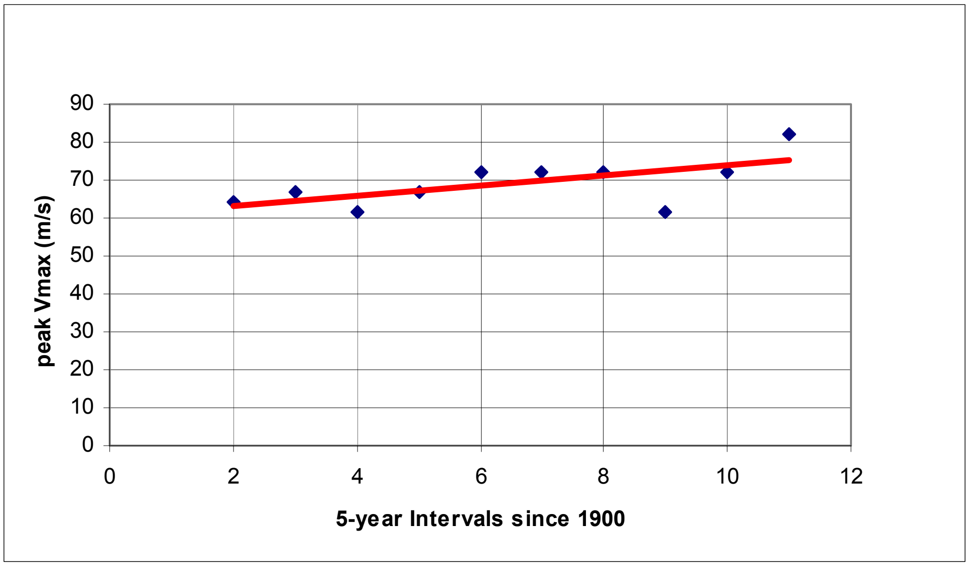



Figure 5. Temporal Variation of 5-Year Maximum peak $V_{max}$ from 1910-1955 (half cycle period)

2. From historical database determine the peak $V_{max}$ for each storm.
3. Plot values of peak $V_{max}$ to determine best-fit distribution function.
4. Generate random values of peak $V_{max}$ from the distribution equal to number of synthetic storms required. Upper bound value of peak $V_{max}$ is set from Step 1.
5. Carry out steps 2-4 for the minimum distance to the location of interest for each storm ($D_{min}$).
6. Select a storm track from the parent population at random.
7. Assign a random peak $V_{max}$ to the storm and move it so that the new $D_{min}$ is one of the randomly generated values.
8. Scale the $V_{max}$ at each point in the storm by a constant equal to the ratio of the real peak $V_{max}$ to the random peak $V_{max}$.
9. For each storm, compute Central Pressure, $P_c$, using Equation 1 (Banton, 2002):

$$P_c = (a + \alpha) - bV_{max}{}^{(c-\alpha/d)} \quad (1)$$

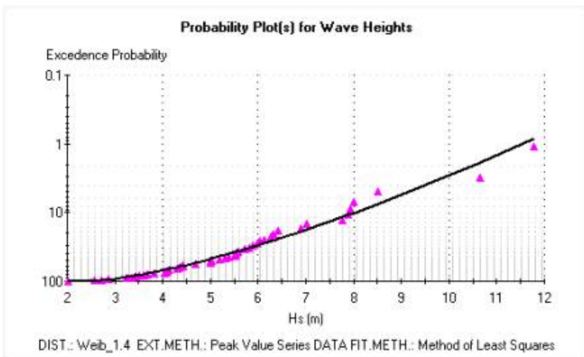
where $a$ = 1014, $b$= 0.029, $c$=1.626, $d$=200 and $\alpha$ is a random variable uniformly distributed in the range [-10,10]. $\alpha$=0 for the expected value of $P_c$. Note that $P_c$ is in mbars, $V_{max}$ in knots and $\alpha$ is randomized for each run.

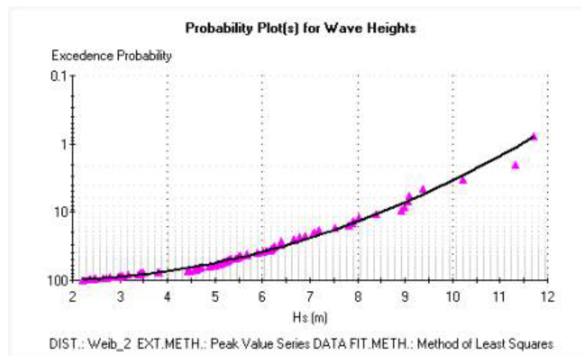
10. Then compute radius to maximum winds ($R_{max}$) using Equation 2 (Banton, 2002):

$$R_{max} = 3 \times 10^{-6}\, e^{\,0.017Pc} \qquad (2)$$

11. Calculate wave heights for each synthetic storm using parametric wave hindcasting techniques. For the case presented here, the model from Cooper (1988) was used.
12. Perform extremal analysis on wave heights.
13. Repeat process several times and average results.

An example of the results of this method is shown alongside predictions for hurricane-generated waves off the south coast of Jamaica. The diagrams below show the excedence plots for the historical approach and for the Monte Carlo approach with a project life up to the year 2020.




A summary of the calculated wave heights is given below in Table 1:

**Table 1. Summary of Calculated Wave Heights**

| Return Period (years) | $H_s$ from historical method (m)<br>Correlation = 0.988 | $H_s$ for Proposed Method (m)<br>Correlation = 0.989 |
|---|---|---|
| 2 | 2.6 | 3.9 |
| 5 | 5.4 | 6.5 |
| 10 | 6.8 | 7.8 |
| 20 | 8.0 | 8.9 |
| 25 | 8.4 | 9.2 |
| 50 | 9.5 | 10.2 |
| 100 | 10.6 | 11.0 |

## CONCLUSIONS

The past century of hurricane statistics has been examined and both multi-decadal and long-term trends have been observed in hurricane frequency and intensity. Of interest is the finding that the average number of hurricanes per year is expected to increase from 8-10 to between 11 and 12 over a 100-year period.

Resulting from these findings, a methodology is proposed for developing design wave criteria for the Caribbean region, which takes into account the anticipated increases in frequency of occurrence and storm intensity.

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