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# The Impact of Global Warming on Hurricane Intensity

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**Abstract**. The inner correlation between hurricane activities and the deterioration of global warming has long been a hot issue in environment science. In this article, we structure a novel model to assess the linkage between the strength of global hurricane activities and the extent of global warming. Its novelty falls into two aspects. First, we innovatively propose hurricane intensity index and global warming index as a measurement according to their formation principle. Second, regression analysis and relationship analysis are both adopted to analyse their relationship. Through validation, our conclusion that global warming will exacerbate hurricane intensity is fully credible.

## 1. Introduction

In recent years, the devastating hurricanes have been people's major concern. It becomes a top priority for people to find out the underlying cause for these catastrophes. According to a statement from WMO Expert Team, model simulations indicate that hurricanes in a warmer climate are likely to become more intense. Future projections based on theory and high-resolution dynamical models indicate that global warming will cause the averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2–11% by 2100 [1]. So should global warming take the blame for these intense hurricanes?

To explore the correlation between hurricane intensity and global warming, we firstly propose *the hurricane intensity function* based on its forming principle and briefly analyze how hurricanes may get affected by global warming. It is notable that here we choose hurricanes on the west coast of America, the most typical ones which are caused by earth rotation and warm sea water, as our research object. Secondly, we design two indexes to separately measure the intensity of hurricanes and the extent of global warming. By simulating on computer, we can get the general changing tendency of hurricane intensity and global warming in the past decades.

Then, we can build the relational function between hurricane intensity and global warming. Using *regression analysis* and *relationship analysis*, it's not hard for us to conclude that the intensifying of global warming will dramatically increase the hurricane intensity. In order to demonstrate the reliability of our model, we validate the model with grey prediction method to conduct autoregressive predictions on each variable. Finally, we employ error analysis to assess the accuracy. It turns out that our model is credible.

## 2. Model Theory

### *2.1. The hurricane intensity function*

Hurricanes, also known as tropical cyclone, is a rapidly rotating storm system characterized by a low-pressure center, a closed low-level atmospheric circulation, strong winds, and a spiral arrangement of thunderstorms. Its forming process is as follows:

Firstly, the temperature of a certain sea area soars rapidly due to long-time exposure in the sun, resulting in a low-pressure area. The pressure differences between the low-pressure center and the atmosphere nearby is the inner force to motivate a hurricane. Driven by pressure difference, the surrounding air in atmosphere moves towards the low-pressure center. The movement is affected by earth rotation, thus forming a rotating airflow, which is counterclockwise in the northern hemisphere whereas clockwise in the southern hemisphere. Because of the rotation, the low-pressure center can maintain for a long time, thus form a hurricane.

According to the information above, we can try to define the hurricane intensity from the following perspectives.

*2.1.1. Atmospheric pressure.* It is obvious that the formation of hurricanes has a lot to do with the decrease of air pressure over the sea level. The wind pressure will rise considerably when the low-pressure air flow reaches the high-pressure area, thus causing strong wind. Similarly, hurricanes are whirl wind of which the wind velocity surpasses $32.6\, m/s$ . So, we can use wind velocity to measure the hurricane intensity. And we will proceed as follows:

Wind pressure is the pressure wind presses on the perpendicular plane of the air flow. According to the wind-pressure relationship in Bernoulli equation, we can know that the dynamic pressure of wind is:

$$p_w = 0.5 \cdot \rho \cdot v^2 \qquad (1)$$

Where $p_w$ presents wind pressure [ $kN/m^2$ ], $\rho$ represents air density [ $kg/m^3$ ], and $v$ is wind velocity [ $m/s$ ].

From the relationship between air density and unit weight: $r = \rho \cdot g$ , we can get that:

$$\rho = r/g \qquad (2)$$

Where $\rho$ is air density and $r$ is unit weight.

We apply equation (2) to (1),then:

$$p_w = 0.5 \cdot r \cdot \frac{v^2}{g}$$

This is the Standard Wind Pressure Formula. In the standard condition, where Barometric pressure is 1013 $hPa$ , atmospheric temperature is $15\,^{o}C$ , unit weight: $r = 0.01225$ [ $kN/m^2$ ] and gravity acceleration $g = 9.8$ [ $m/s^2$ ], we can obtain that:

$$p_w = \frac{v^2}{1600} \qquad (3)$$

We can find from equation (3) that the square of the wind velocity is proportional to wind pressure, which means that $v$ is proportional to $\sqrt{p_w}$ .

From the equations above, we can summarize that the strengthening of hurricanes is associated with wind pressure, which equals to the decreasing of pressure over the sea. In the meantime, the decline of atmospheric pressure over the sea is affected by many factors simultaneously, among which sea water temperature and air humidity play the most important roles. There is no doubt that global warming will rise sea water temperature and hasten ocean evaporation. We will analyse the effects of these two factors on the pressure over the sea respectively.

As for sea water temperature, we can use the air temperature over the sea in replacement of the sea water temperature and analyse how it influences the atmospheric pressure.

When the volume is fixed, the increase of temperature can agitate the gas molecules. As a result, the pressure goes up. However, the number of molecules in a fixed volume will decline accordingly, leading to the decrease of pressure. As we know, drop in number of gas molecules has the bigger effect, so the increase in temperature will decrease the atmospheric pressure. From the work of Emanuel [2], we can find that pressure is linear to the temperature of the third power. Hence we suppose that the impact factor is $aT^{\frac{3}{2}}$, where $T$ represents temperature and $a$ is a constant that is greater than 0.

As for air humidity, it's universally acknowledged that atmosphere contains a considerable amount of vapor and dust. Air with little moisture is defined as "dry air", and "wet air" represents air with more moisture correspondingly. There are $28.966\,mol$ molecules in every unit of "dry air", and in vapor it is $18.016\,mol$ per unit. So we can conclude that "dry air" molecule is heavier than vapor molecule. In addition, the density of "dry air" is also bigger than that of vapor. Moreover, the density of vapor is only about $62\%$ of "dry air" density.

Since the atmosphere is in an open space around the earth, there is no specific boundary to constrain its motion, which makes it different from the gas in the sealed container. For a sealed container, as long as the gas is not saturated, the pressure of the gas will increase as we add vapor into the container. However, things are quite different with atmosphere. When air humidity in a certain region rises, the molecule in the "wet air", including air molecule and vapor molecule, will spread towards the surrounding regions. As a result, there will be less "dry air" in this region, meanwhile its moisture content is larger than that in the surrounding area, thus the "wet air" density in this area is lower than the "dry air" density in other areas.

SJ Camargo's work shows that pressure is linear to the relative air humidity of the third power when atmospheric pressure is at $600\,hPa$ [3]. So we suppose that the impact factor is $bH^{\frac{3}{2}}$, where $H$ denotes the relative humidity, $b$ is a constant and $b > 0$.

*2.1.2. Wind shear.* Wind shear is a difference in wind speed or direction over a relatively short distance in the atmosphere. The formation of hurricanes requires relatively low values of vertical wind shear so that their warm core can remain above their surface circulation center, otherwise hurricanes may weaken or dissipate. Here we only study the influence of vertical wind shear, which plays the most significant role in the formation of hurricanes [4].

Scientific researches have proved that the wind shear index and temperature are negatively correlated. That means when the temperature is low, the wind shear index will remain at a high level, and it can become small at a relative high temperature. Therefore, we can infer that the wind shear is small in the day and it ascends at night. When the night falls, the ground temperature decreases, the cold air density becomes larger, however the air flow gets smaller. On the contrary, the upper air density is small, but the air flow is quite large. There exists a big difference in the velocity of air flow in the upper and lower atmosphere, thus the wind shear is greater at night. In the daytime, the sun irradiates the ground, leading to the rise in ground temperature. The upper and lower air flow are more active and the difference between their velocity is very small, thus the wind shear in the day is small, too. SJ Camargo has found from the overfitting of statistical data that the intensity of hurricanes and the combined factors of vertical wind shear $(1+0.1V_{shear})^{-2}$ are approximately linear, here $V_{shear}$ represents strong vertical wind shear, namely the vertical wind shear that exceeds $10\,m/s$.

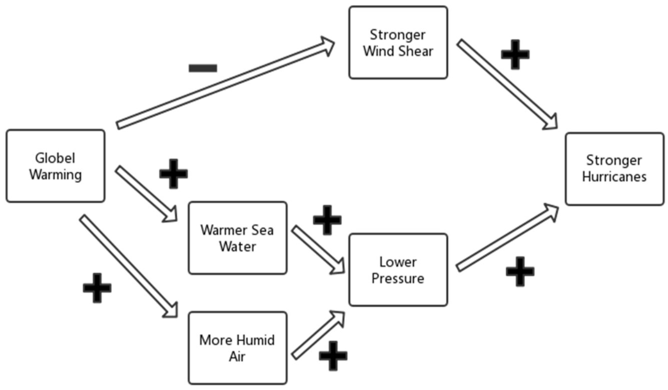


Figure 1. Element relationship diagram.

*2.1.3. The hurricane intensity function.* Based on the analysis above, we can obtain element relationship diagram in figure 1 as well as the Hurricane Intensity Function:

$$HS = aT^3 + bH^3 + c(1+0.1V_{shear})^{-2} \quad (4)$$

Where $HS$ denotes hurricane intensity.

*2.2. Hurricane intensity index*

To better describe the intensity of the hurricanes, we attempt to design the Hurricane Intensity Index.

Different from tornados, the destructive power of hurricanes does not lie in its vorticity but in wind velocity and wind pressure. Our index will be built on the two elements. Using linear relationship, we can get the following equation:

$$HS = ev + fp_w$$

Where $HS$ denotes hurricane intensity, $v$ denotes wind velocity, $p_w$ is wind pressure. $e$ and $f$ are both constants.

In order to facilitate observation, we constrain $HS$ in $[0,100]$. Considering that the wind velocity has greater influence on hurricanes than wind pressure, we adjust the index according to the data of wind velocity and wind pressure, and finally set $e = 0.78$, $f = 0.49$, then we have:

$$HS = 0.78v + 0.49p_w \quad (5)$$

*2.3. Global Warming Index*

Since the global average temperature is rising continually in the past decades, it's inappropriate for us to merely use temperature to estimate the extent and rate of global warming. Thus, we design the global warming index to measure the change in the extent of global warming:

$$J = T_n - \overline{T}, \overline{T} = \frac{\sum_{t=1}^{n-1} T_t}{n-1} \quad (6)$$

Where $J$ is the global warming index, $T_n$ is the global average temperature this year; $\overline{T}$ represents the average temperature in a long period up to last year.

## 3. Model Solution

*3.1. Data collection*

We select the annual average of statistics on climate and ocean conditions of American west coast during the past 30 years (1985-2015). All the data used comes from Met Office Hadley Centre Observations Datasets [5]. As for few missing data, we adopt the average filling method for completion.

### 3.2. *Trend analysis*

8As for hurricane intensity, we will quote hurricane intensity index $HS$ for calculation. We put the wind velocity and wind pressure data into equation (5), and get the figure 2 via *MATLAB*:

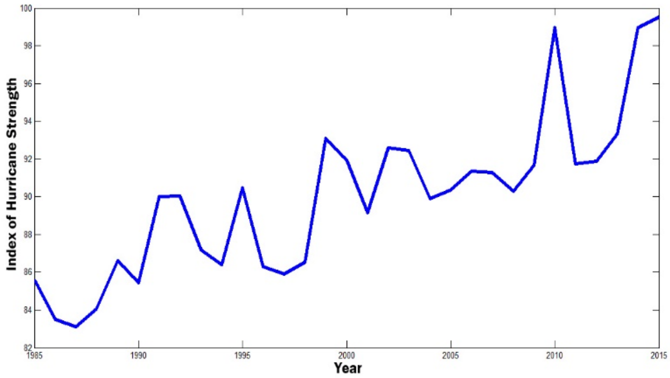


Figure 2. Hurricane Intensity Tendency Chart.

We can conclude from figure 2 that the hurricane intensity on the west coast of US is increasing ceaselessly in the past 30 years.

Likewise, we can get the global warming tendency chart in *MATLAB* with equation (6):

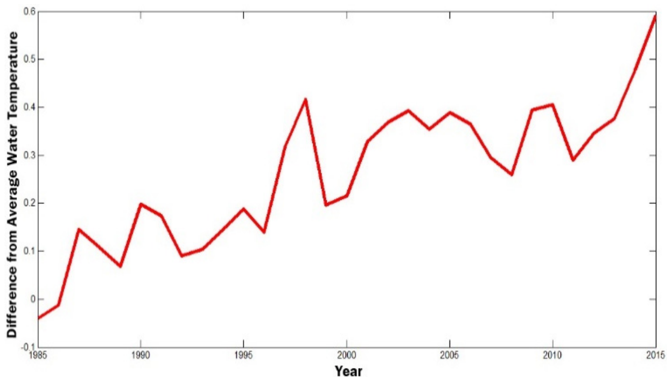


Figure 3. Global Warming Tendency Chart.

As the chart depicts, global warming is becoming worse and worse.

## 4. Regression Analysis

To begin with, we can infer qualitatively that global warming accounts for the increase in sea water temperature, air humidity as well as vertical wind shear. In order to further exemplify the extent of global warming and the strength of global hurricane activities, we will use equation (4) for regression analysis.

We can use the regression function in *MATLAB*, then we'll get:

Table 1. Result of Regression Analysis.

| Parameter | Predicted value |
|---|---|
| $a$ | 0.0012 |
| $b$ | $9.88\times10^{-5}$ |
| $c$ | 9.03474 |

$$R^2 = 0.9385$$
$$F = 221.7632$$
$$p < 0.0001$$

In table 1, $R^2 = 0.9385$ means the dependent variable $y$ in the hurricane intensity index equals to 93.85%. Additionally, the statistics value of $F$ far exceeds the threshold in the test, and $p$ is much smaller than the confidence level $\alpha$=0.05 . Therefore, this model is feasible.

Finally, we can draw the conclusion that the relationship between hurricane intensity index and seawater temperature, relative humidity and strong vertical wind shear strength is as follows:

$$HS = 0.0012\cdot T^3 + 9.98\times10^{-5}\cdot H^3 + 9.03474\times (1+0.1V_{shear})^{-2} \quad (7)$$

## 5. Relationship Analysis

We can find from equation (7) that the intensity of hurricane is positively correlated with seawater temperature, relative humidity, and strong vertical wind shear strength. But we should discuss it in two aspects. On the one hand, hurricane intensification is exacerbating because of the increase in seawater temperature and relative humidity which result from global warming. On the other hand, global warming will weaken the strong vertical wind shear, thus decreasing the hurricane intensity. However, according to the power series and coefficient of each parameters in equation (7), we know that sea water temperature and relative air humidity have a stronger influence on hurricane intensity than wind shear [6]. So, we can conclude that global warming will exacerbate hurricane intensity.

## 6. Model Validation

We will adopt grey prediction method to conduct autoregressive predictions on each variable for validating. Firstly, we calculate $HS$ , $T$ , $H$ , $V_{shear}$ in the following 10 years. Then we put the predictive dependent value into equation (4) and get the predictive value of $HS$ . Finally, we draw the autoregressive curve of $HS$ and find the error in predictive value of $HS$ to validate the model.

### *6.1. Grey prediction method*

Grey prediction method means establishing a grey differential prediction model with limited incomplete information to make a fuzzily long-term description of the regularity in the development of things. The prediction model is a fitting parameter model in which we generate a regular sequence by accumulating raw data and get the predicted value by fitting the function curve.

### *6.2. Model construction*

Firstly we record $x^{(0)}$ as the original sequence:

$$x^{(0)} = (x^{(0)}(k), k = 1, 2, \cdots, n) = (x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n))$$

Secondly we record $x^{(1)}$ as the generated sequence:

$$x^{(1)} = (x^{(1)}(k), k = 1, 2, \cdots, n) = (x^{(1)}(1), x^{(1)}(2), \cdots, x^{(1)}(n))$$

If the relationship between $x^{(0)}$ and $x^{(1)}$ satisfies the equation:

$$x^{(1)}(k) = \sum x^{(0)}(i)$$

Then we think an accumulation is generated.

Next, we adopt Grey GM (1,1) Model to predict the growth mode of sequence $x^{(0)}$ in *MATLAB* and get table 2

Table 2. Each Element's Results of Grey Prediction Method in 10 Years.

| Year | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|
| *HS* | 96.448 | 96.874 | 97.303 | 97.733 | 98.166 |
| *T* | 25.153 | 25.17 | 25.188 | 25.206 | 25.224 |
| *H* | 91.849 | 92.03 | 92.212 | 92.393 | 92.575 |
| $V_{shear}$ | 17.131 | 16.927 | 16.723 | 16.520 | 16.316 |
| Year | 2021 | 2022 | 2023 | 2024 | 2025 |
| *HS* | 98.6 | 99.036 | 99.474 | 99.914 | 100.356 |
| *T* | 25.241 | 25.259 | 25.277 | 25.295 | 25.313 |
| *H* | 92.757 | 92.94 | 93.123 | 93.306 | 93.49 |
| $V_{shear}$ | 16.112 | 15.909 | 15.705 | 15.501 | 15.298 |

We put the value of three parameters above in equation (7) and compare it with the auto regression of $HS$ . The result is as follows:

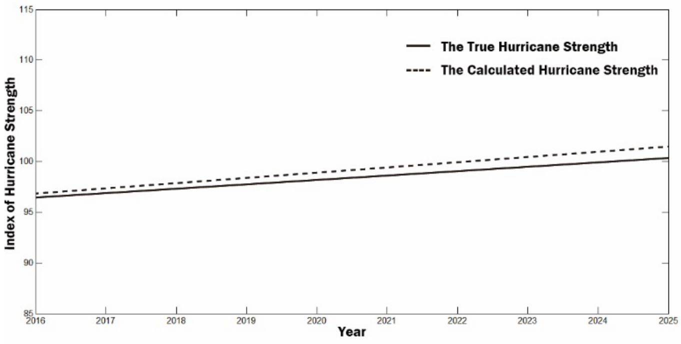


Figure 4. The Real Hurricane Intensity and The Calculated Value

As is depicted in figure 4, the fitting degree is very high, even the maximum error is smaller than 1.63. So, it's advisable for us to use equation (7) to simulate the relationship between the three parameters and the hurricane intensity.

*6.3. Validation on grey prediction model*

Our tests on grey prediction model consist of relative residual test, level deviation test and posterior difference test.

*6.3.1 Relative residual.*

$$\varepsilon(i) = \frac{x^{(0)}(i) - \hat{x}^{(0)}(i)}{x^{(0)}(i)}, i = 1, 2, 3, \ldots, n$$

*6.3.2 Level deviation.*

$$\rho(i) = 1 - \left(\frac{1 - 0.5a}{1 + 0.5a}\right)\lambda(i), i = 1, 2, 3, \ldots, n$$

*6.3.3 Standard deviation of original sequence.*

$$S_1 = \sqrt{\frac{\sum [x^{(0)}(i) - \overline{x}^{(0)}]^2}{n-1}}$$

*6.3.4 Residual.*

$$\Delta^{(0)}(i) = x^{(0)}(i) - \hat{x}^{(0)}(i)$$

*6.3.5 Standard deviation of the absolute error sequence.*

$$S_2 = \sqrt{\frac{\sum [\Delta^{(0)}(i) - \overline{\Delta}^{(0)}]^2}{n-1}}$$

*6.3.6 Variance ratio.*

$$C = \frac{S_2}{S_1}$$

*6.3.7 Small error probability.* We set $e_i = \left|\Delta_i^{(0)} - \bar{\Delta}^{(0)}\right|$ and $S_0 = 0.6745 S_1$, then we have :

$$P = p\{e_i < S_0\}$$

*6.4. Validation standard*

If $\varepsilon(i) \le 0.2$ ,we think the result has met the general standard; if $\varepsilon(i) \le 0.1$ ,we believe the result has achieved a high standard.

If $\rho(i) \le 0.2$ ,we think the result has met the general standard; if $\rho(i) \le 0.1$ ,we believe the result has achieved a high standard.

The standard posterior difference table is as follows:

Table 3. The Posterior Difference.

| P | C | Posterior difference |
|---|---|---|
| >0.95 | <0.35 | Excellent |
| >0.80 | <0.50 | Good |
| >0.70 | <0.65 | Qualified |
| ≤0.70 | ≥0.65 | Failed |

And after testing we get:

Table 4. Validation Result.

| Parameters | Relative Residual | Level Deviation | Variance Ratio | Small Error Probability | Error Accuracy Grade |
|---|---|---|---|---|---|
| $HS$ | all<0.1 | all<0.1 | 0.1117 | 1 | Excellent |
| $T$ | all<0.1 | all<0.1 | 0.4045 | 0.9286 | Good |
| $H$ | all<0.1 | all<0.1 | 0.3067 | 0.9513 | Excellent |
| $V_{shear}$ | all<0.1 | all<0.1 | 0.3895 | 0.9482 | Good |

By comparison we can see that results have achieved a good fitting degree, so the validating method is suitable for testing.

## 7. Conclusion

In this paper, we propose a novel model aiming to demonstrate the relationship between hurricane intensity and global warming. By analysing the forming process of hurricane, we establish the hurricane intensity function based on its main causes. Qualitatively we can infer that hurricanes will intensify with the increasing global warming. In order to prove our hypothesis, we build the global warming index and hurricane intensity index to quantificationally describe their changes in the last decades. After drawing their tendency chart in *MATLAB*, we find that hurricane intensity and global warming both increase.

Regression analysis conducted on our function helps us complete the hurricane intensity function and make relationship analysis on hurricane intensity and global warming. We conclude from the function that global warming will exacerbate hurricane intensity. This conclusion has passed our validation on the grey prediction model, which means our model is completely advisable. In the future, we will further study the effect that global warming brings on other nature disasters.

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