Statistical Error in Forecasted Tracks with Hurricane Katrina and Hurricane Rita using the Global Forecasting System (GFS) Model

Graylen Boone
Marvin Boyd
Tara Bradley
Katie Craven

Dr. S. Ghosh
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Term Project
Executive Summary

It is an understood fact that hurricane tracks are often inaccurate, unreliable and hard to predict. For this term project, the forecasted tracks for Hurricane Katrina and Hurricane Rita were analyzed for accuracy and compared to the verified tracks that were issued by the National Hurricane Center. This was done in order to determine whether forecast models are accurate in their predictions. This forecasted track error was obtained by comparing the global forecast system (GFS) modeled track to the actual track using the geodesic distance based on a latitude and longitude coordinate system. For each hurricane, the 72, 48, and 24-hr model runs were extracted and examined, based on a 6-hr increment established by the GFS model. It was found that the GFS model provides a fairly accurate estimate of the landfall location, based on the results that were found from examining the data. In the case of Hurricane Katrina, the 72-hr forecast exhibited a 75km error, whereas the 48 and 24-hr forecasts produced errors of 50 and 10 km, respectively. Similar results were discovered with Hurricane Rita, with errors of 80, 40 and 10 km being associated with the 72, 48 and 24-hr forecasts. It is clear that the variability in the error in location of landfall diminished with time as the hurricane moved closer to land. Also, the variability in the range of error also decreases in this manner. Although each forecast made by the GFS model as associated with error, it should be recognized that the short-term forecasts that were made were fairly accurate for both Hurricane Katrina and Hurricane Rita.
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Statistical Analysis of Forecasted Hurricane Tracks
I. Description of Data

a. Scientific Background

Hurricane Katrina and Hurricane Rita were both intense hurricanes of the 2005 Atlantic Hurricane Season, notably the most active hurricane season on record. These storms rank in the Top-10 for intensity, and when paired, are the costliest storms of all time. Hurricane Katrina made landfall in August 2005 east of New Orleans, LA, causing widespread damage, hysteria and causalities to Louisiana and surrounding areas. Hurricane Rita moved onshore in September 2005 near the Texas-Louisiana border, bringing extensive devastation just one month after Hurricane Katrina issued its assault along the Gulf Coast. Both of these storms are potentially the largest impacting storms on the US economy with energy concerns that affected the entire nation. Because hurricanes can cause considerable damage to life and property, it is important to be able to properly predict these events and where they will have a significant impact. The primary tools for forecasting hurricane tracks are forecast models, including the Global Forecasting System (GFS) and the North American Mesoscale Model (NAM). Since the GFS model usually provides a more accurate forecast for large scale movement across the globe, given that it is a wave-spectrum model, this analysis will focus on the forecast track error with this model instead of the NAM model, which is more accurate with smaller scale features. This study will focus on the question as to whether the GFS model produces accurate forecast tracks for tropical system, based on the error calculated by comparing the tracks produced by this model with the verified track that each storm exhibited.

b. Major Variables

In order to calculate the error between the forecasted tracks and the verified tracks for Hurricane Katrina and Hurricane Rita, the geodesic distance, or the great-circle distance, was first used to gauge the distance between the latitude and longitude coordinates that marked the center of each storm at given times. Geodesics on the sphere are the great circles, which allows for all calculations to be considered on an arc, representing the earth, rather than a straight line.

For each storm, the times used were in reference to the time at which the storm made landfall. Numerical model data from the Iowa State GEMPAK Archive was loaded into the
GARP modeling package to be run and analyzed. Once the data was made available, the 72, 48, and 24-hr model runs were used to analyze the GFS forecasted tracks for each storm. Additionally, to have more data for comparison, “reference” landfalls were also established, which marked days that were up to 3 days prior to the actual landfall date. Since the GFS issues a forecast for every 6 hours, these times were extracted and then matched up with the times on the verified tracks. Once the times were established, the central pressure was used to determine the eye of the storm for the forecasted tracks and to extrapolate the latitude and longitude coordinates for the specific location. Using the geodesic distance, the differences in latitude and longitude points were calculated between the forecasted and verified tracks in which times coincided. After this data was collected, the errors between the 72, 48, and 24-hr model runs were compared with one another in order to determine which run provided a better forecast for each hurricane.

II. Statistical Analysis

In order to examine the data that was obtained from the forecasted and verified tracks, the R plotting package was utilized to obtain a statistical analysis of each hurricane. By doing this, an in-depth inquiry took place by using different parameters and techniques that R supports. It should be noted that similar methods were used for Hurricane Katrina and Hurricane Rita so that each storm might be compared in an analogous fashion.

a. Hurricane Katrina

To begin the analysis, scatter plots were made in order to examine the trends with the 72, 48 and 24-hr forecasts with Hurricane Katrina. All R code that was used to create each figure can be references in the appendix. Fig. 1 shows the 72-hr forecast scatter plot, using the actual date of landfall as a reference.
Fig. 1. Scatter plot for Hurricane Katrina, 72-hr forecast error, 26-29 August, 2005.

Similar scatter plots were made for the 48 and 24-hr forecast, both of which use the actual date of August 29th as the landfall of Hurricane Katrina. These can be seen in figures 2 and 3.

Fig. 2. Scatter plot for Hurricane Katrina, 48-hr forecast error, 27-29 August, 2005.
The numerical summaries were also obtained in order to examine these trends with each forecast in a different and more concise manner. Table 1 is a summary of the statistical output from the 72-hr forecast in fig. 1. The R code for this summary can be seen in the appendix.

<table>
<thead>
<tr>
<th>Minimum</th>
<th>1st Qua.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qua.</th>
<th>Maximum</th>
<th>NA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.54</td>
<td>72.50</td>
<td>116.00</td>
<td>103.30</td>
<td>147.50</td>
<td>170.10</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Table 1. Numerical summary of Hurricane Katrina, 72-hr forecast, 26-29 August, 2005.

These numerical summaries include the lowest and highest value observed in the specified dataset, the 1st and 3rd quantile value, the median, mean and the number of NA values that are present in the data. The NA values occur in each dataset when there appeared a void in the amount GFS numerical data at a certain time. The numerical summaries for the 48 and 24-hr forecasts can be found similarly in tables 2 and 3.

<table>
<thead>
<tr>
<th>Minimum</th>
<th>1st Qua.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qua.</th>
<th>Maximum</th>
<th>NA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.72</td>
<td>51.97</td>
<td>74.79</td>
<td>66.65</td>
<td>80.54</td>
<td>122.10</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Table 2. Numerical summary of Hurricane Katrina, 48-hr forecast, 27-29 August, 2005.
To wrap up the statistical analysis Hurricane Katrina, boxplots were utilized and examined to compare the each of the 72, 48 and 24-hr forecasts. These boxplots can be seen in figures 4, 5 and 6, respectively.

**Table 3.** Numerical summary of Hurricane Katrina, 24-hr forecast, 28-29 August, 2005.

<table>
<thead>
<tr>
<th>Minimum</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; Qua.</th>
<th>Median</th>
<th>Mean</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; Qua.</th>
<th>Maximum</th>
<th>NA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.97</td>
<td>16.63</td>
<td>18.53</td>
<td>19.07</td>
<td>20.95</td>
<td>32.25</td>
<td>8.00</td>
</tr>
</tbody>
</table>

**Fig. 4.** Boxplot for Hurricane Katrina, combined 72-hr forecast errors.

**Fig. 5.** Boxplot for Hurricane Katrina, combined 48-hr forecast errors.

Statistical Analysis of Forecasted Hurricane Tracks
Statistical Analysis of Forecasted Hurricane Tracks

To summarize the primary findings from each boxplot with Hurricane Katrina, figure 7 shows the least 72, 48 and 24-hr forecast errors compared to one another.

Fig. 6. Boxplot for Hurricane Katrina, combined 24-hr forecast errors.

Fig. 7. Boxplot for Hurricane Katrina, 72, 48 and 24-hr forecasts with least errors.
b. *Hurricane Rita*

The analysis of Hurricane Rita was approached in a similar way, with scatter plots created to examine the trends with the 72, 48 and 24-hr forecasts. All R code that was used to create each figure for Hurricane Rita can also be references in the appendix. Fig. 8 shows the 72-hr forecast scatter plot, using the actual date of landfall as a reference.

![Fig. 8. Scatter plot for Hurricane Rita, 72-hr forecast error, 21-24 September, 2005.](image)

Similar scatter plots were made for the 48 and 24-hr forecast, both of which use the actual date of September 24th as the landfall of Hurricane Rita. These can be seen in figures 9 and 10.

![Fig. 9. Scatter plot for Hurricane Rita, 48-hr forecast error, 22-24 September, 2005.](image)
The numerical summaries were obtained to examine these trends with each forecast in a different and more concise manner. Table 1 is a summary of the statistical output from the 72-hr forecast in fig. 1. The R code for this summary can be seen in the appendix.

<table>
<thead>
<tr>
<th>Minimum</th>
<th>1st Qua.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qua.</th>
<th>Mas</th>
<th>NA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.00</td>
<td>70.92</td>
<td>109.40</td>
<td>114.00</td>
<td>145.30</td>
<td>234.90</td>
<td>3.00</td>
</tr>
</tbody>
</table>


These numerical summaries include the lowest and highest value observed in the specified dataset, the 1st and 3rd quantile value, the median, mean and the number of NA values that are present in the data. The NA values occur in each dataset when there appeared a void in the amount GFS numerical data at a certain time. The numerical summaries for the 48 and 24-hr forecasts can be found similarly in tables 5 and 6.

<table>
<thead>
<tr>
<th>Minimum</th>
<th>1st Qua.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qua.</th>
<th>Mas</th>
<th>NA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.09</td>
<td>31.29</td>
<td>39.48</td>
<td>44.70</td>
<td>48.41</td>
<td>88.85</td>
<td>5.00</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Minimum</th>
<th>1st Qua.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qua.</th>
<th>Mas</th>
<th>NA’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.38</td>
<td>36.88</td>
<td>38.55</td>
<td>38.51</td>
<td>40.18</td>
<td>44.57</td>
<td>9.00</td>
</tr>
</tbody>
</table>

To wrap up the statistical analysis Hurricane Rita, boxplots were utilized and examined to compare the each of the 72, 48 and 24-hr forecasts. These boxplots can be seen in figures 11, 12 and 13, respectively.

Fig. 11. Boxplot for Hurricane Rita, combined 72-hr forecast errors.

Fig. 12. Boxplot for Hurricane Rita, combined 48-hr forecast errors.
To summarize the primary findings from each boxplot with Hurricane Rita, figure 14 shows the least errors of the 72, 48 and 24-hr forecast compared to one another.

Fig. 13. Boxplot for Hurricane Rita, combined 24-hr forecast errors.

Fig. 14. Boxplot for Hurricane Rita, 72, 48 and 24-hr forecasts with least errors.
III. Major Findings

Looking at the storms individually, there is definitely a linear trend in the means of each forecast. There is also an observed increase in accuracy for shorter term forecasts. This occurs even though there are some inconsistencies in the data where one of the seventy-two hour forecasts and one of the twenty-four hour forecasts actually improve through their respective forecasts. The reason for these forecast inconsistencies may be due to the forecasted track actually crossing paths with the verified track. This is turn gives you a cancellation of the data points. If we had the 96 and 108 hour forecast points you would see that there would be a drastic increase in error by the fourth and fifth day. Unfortunately, the model archive only carries a maximum of 72 hour forecasts.

Visually, the 72 hour box plots show a linear trend and improving accuracy as Hurricane Katrina approached the Louisiana/Mississippi shore. The variance, also, decreases the closer to landfall. The mean for the 48 hour box plot doesn’t follow the linear trend, but the variance still decreases for forecasts, temporally, closer to landfall. Finally, the 24 hour box plots shows a more rapid increase in accuracy as the days approach landfall; this variance and inaccuracy appear to decay almost exponentially.
For Hurricane Rita, there tends to be a large amount of initial error in the forecasts. This is mostly due to two factors, first being the human factor. When we coded the data in the table, we didn’t have any closed isobars (lines of equal surface pressure), to visually guide us to the center of the tropical disturbances. We estimated the center by interpolating the center to be in the relative center of the lowest isobar. This proved a bit inaccurate as an approach to determining the center of circulation; overlaying some satellite imagery may have improved this error. Secondly, there is likely a bit of model initialization error. The model didn’t handle the initial position, but autocorrected shortly thereafter using satellite and RADAR as a sieve. Otherwise the error increased extremely linearly as the forecasts ran to 72, 48, and 24 hours.

Unfortunately, there was another issue with the model. The 72 hour forecasts that predicted land fall actually proved to be less accurate than the 72 hour forecasts that did not include land fall. This is an anomaly that the data cannot explain through statistical interpretation.

Even given the discrepancies above, our hypothesis was proven accurate. As time decreased, the forecast went from a seventy-two hour forecast to a twenty-four hour forecast and the averages for distance error decreased significantly.

A linear model fit this nearly perfectly and explained 99.86 percent of the data. This is depicted in figure 15

IV. Discussion

This study proved to have limitations that could have provided a substantial amount of error in the results obtained. While error is usually associated with any study that is personally conducted, it is important to note the possible sources so that future studies may be more properly executed and examined.

Indiscretions with human extrapolation of the latitude and longitude coordinates when finding the center storm location in GARP are possible causes of the error associated with this study. When the data was originally loaded into the GARP plotting package and analyzed, the lowest central pressure and the coordinates of this point were personally estimated. It is likely that these points were not the exact location of the lowest central pressure given for the storm at that time.

Once the coordinates were obtained, the distance between the forecasted and verified tracks was calculated by the use of a geodesic calculator, which finds the shortest distance between any
two points on a sphere. There is no doubt that this procedure could exist as a source of error when the spherical coordinates are forced down to a flat surface. This loses the resolution that would otherwise be present on the original curved surface. The differences between the points are thus exaggerated as an effect.

By using the GFS model for each selected time, there remains a problem of a lack of data as the forecast runs draw to a close. This defect in the system produces missing data that would be beneficial to a complete analysis of the 72-hr forecast run for both Hurricane Katrina and Hurricane Rita. This issue was not evident in the 48 and 24-hr forecast, and the model runs issued forecasts every 6 hours. If the 72-hr forecast included 6 hour forecasts in the final 24 hours of the model run, there might be less error in interpolating the results for error closer to when the hurricanes are projected to make landfall.

Finally, there may be a biased result to surface from our study since only two chosen storms were selected from one Atlantic hurricane season. Both Hurricane Katrina and Hurricane Rita were extremely powerful storms, and this could play a part in how well the GFS model projects its landfall location. Future investigation would be needed to determine whether or not the model does an adequate job forecasting smaller, less intense tropical cyclones.
V. Appendix

a. Hurricane Katrina

A1. R code for 72 Hour Forecast Error from August 24th through August 27th
> katrina=read.table("clipboard",header=T)
> time=katrina$time
> a=katrina$a
> b=katrina$b
> c=katrina$c
> d=katrina$d
> e=katrina$e
> f=katrina$f
> g=katrina$g
> h=katrina$h
> i=katrina$i
> good=which(katrina>-100)
> a.good=a[good]
> b.good=b[good]
> c.good=c[good]
> d.good=d[good]
> e.good=e[good]
> f.good=f[good]
> g.good=g[good]
> h.good=h[good]
> i.good=i[good]
> time.good=time[good]
> plot(time.good, a.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 72-hr Forecast Error, August 24-27")

VI. Figure A1.1. This produced was produced using the R code from A1.
A2. R code for 72 Hour Forecast Error from August 25th through August 28th
> plot(time.good, b.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 72-hr Forecast Error, August 25-28")

VII. Figure A2.1. This figure was produced using the R code from A2.

VIII.

A3. R code for 72 Hour Forecast Error from August 26th through August 29th
(Reference to Fig. 1)
> plot(time.good, c.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 72-hr Forecast Error, August 26-29")

A4. R code for 48 Hour Forecast Error from August 25th through August 27th
> plot(time.good, d.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 48-hr Forecast Error, August 25-27")
IX. Figure A4.1. This figure was produced using the R code from A4.

X. A5. R code for 48 Hour Forecast Error from August 26th through August 28th
> plot(time.good, e.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 48-hr Forecast Error, August 26-28")

XI. Figure A5.1. This figure was produced using the R code from A5.

XII. A6. R code for 48 Hour Forecast Error from August 27th through August 29th
(ref. to Fig. 2)
> plot(time.good, f.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 48-hr Forecast Error, August 27-29")
A7. R code for 24 Hour Forecast Error from August 26th through August 27th

```r
> plot(time.good, g.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 24-hr Forecast Error, August 26-27")
```

![Hurricane Katrina: 24-hr Forecast Error, August 26-27](image)

XIII. Figure A7.1. This figure was produced using the R code from A7.

A8. R code for 24 Hour Forecast Error from August 27th through August 28th

```r
> plot(time.good, h.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 24-hr Forecast Error, August 27-28")
```

![Hurricane Katrina: 24-hr Forecast Error, August 27-28](image)
XV. Figure A8.1. This figure was produced using the R code from A8.

A9. R code for 24 Hour Forecast Error from August 28th through August 29th (ref. to Fig. 3)
> plot(time.good, i.good,xlab="Hours", ylab="Error in km")
> title("Hurricane Katrina: 24-hr Forecast Error, August 28-29")

A10. R code and values for Summary of Indices in A1. (refer to Tables 1, 2, and 3)
> summary(a)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
30.10   85.66  167.30  181.60  254.60  394.00    2.00
> summary(b)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
46.80   82.85  139.80  160.40  234.70  325.20    2.00
> summary(c)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
14.54   72.50  116.00  103.30  147.50  170.10    2.00
> summary(d)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
46.80   80.30   98.78  131.40  185.40  242.20    4.00
> summary(e)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
32.93   73.41  117.90  107.80  151.30  165.30    4.00
> summary(f)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
9.72   51.97  74.79  66.65  80.54  122.10    4.00
> summary(g)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
32.93  71.58  117.90  107.80  151.30  165.30    8.00
> summary(h)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
9.72   28.83  51.97  48.29  74.79  76.15    8.00
> summary(i)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
6.97  16.63  18.53  19.07  20.95  32.25    8.00

A11. R code for all 72 Hour Forecasts Error Box Plots (ref. to Fig. 4)
> boxplot(a,b,c, xlab=" 72-hr Forecasts", ylab="Error in km")
> title("Hurricane Katrina: 72-hr Forecasts")

A12. R code for all 48 Hour Forecasts Error Box Plots (ref. to Fig. 5)
> boxplot(d,e,f, xlab=" 48-hr Forecasts", ylab="Error in km")
> title("Hurricane Katrina: 48-hr Forecasts")
A13. R code for all 24 Hour Forecasts Error Box Plots (ref. to Fig. 6)
> boxplot(g,h,i, xlab=" 24-hr Forecasts", ylab="Error in km")
> title("Hurricane Katrina: 24-hr Forecasts")

A14. R code for all 72 Hour Least Error Forecasts Box Plots (ref. to Fig. 7)
> boxplot(c,f,i, xlab=" 72,48 & 24-hr Final Forecasts", ylab="Error in km", col =
(c("gold","red","green")))
> title("Hurricane Katrina: Comparisons of Landfall Forecasts with Least Error")

b. Hurricane Rita

B1. R code for 72 Hour Forecast Error from September 19th through 22nd
> rita=read.table("clipboard",header=T)
> rita
> time=rita$time
> a=rita$X19.22
> b=rita$X20.23
> c=rita$X21.24
> d=rita$X20.22
> e=rita$X21.23
> f=rita$X22.24
> g=rita$X21.22
> h=rita$X22.23
> i=rita$X23.24
> good=which(rita > -100)
> a.good=a[good]
> b.good=b[good]
> c.good=c[good]
> d.good=d[good]
> e.good=e[good]
> f.good=f[good]
> g.good=g[good]
> h.good=h[good]
> i.good=i[good]
> plot(time.good,a.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita:72-hr Forecast Error, September 19-22")
Figure B1.1: This graph was produced from the R code in B1

B2. R code for 72 Hour Forecast Error from September 20th through 23rd
> plot(time.good,b.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita:72-hr Forecast Error, September 20-23")

Figure B2.1: This graph was produced from the R code in B2

B3. R code for 72 Hour Forecast Error from September 21st through 24th (reference fig. 8)
(referencplot(time.good,c.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita:72-hr Forecast Error, September 21-24")

B4. R code for 48 Hour Forecast Error for September 20th through September 22nd
> plot(time.good,d.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita:48-hr Forecast Error, September 20-22")
Figure B4.1: This graph was produced from the R code in B4

**B5. R code for 48 Hour Forecast Error from September 21st through September 23rd**

```r
> plot(time.good,e.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita: 48-hr Forecast Error, September 21-23")
```

Figure B5.1: This graph was produced from the R code in B5

**B6. R code for 48 Hour Forecast Error from September 22nd through September 24th (reference fig. 9)**

```r
> plot(time.good,f.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita: 48-hr Forecast Error, September 22-24")
```

**B7. R code for 24 Hour Forecast Error from September 21st through September 22nd**

```r
> plot(time.good,g.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita: 24-hr Forecast Error, September 21-22")
```
Figure B7.1: This figure was produced using the R code from B7

**B8. R code for 24 Hour Forecast Error from September 22nd through September 23rd**

```r
> plot(time.good,h.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita:24-hr Forecast Error, September 22-23")
```

Figure B8.1: This figure was produced using R code from B8

**B9. R code for 24 Hour Forecast Error from September 23rd through September 24th**

```r
> plot(time.good,i.good, xlab="Hours", ylab="Error in km")
> title("Hurricane Rita:24-hr Forecast Error, September 23-24")
```

**B10. R code and values for Summary of Indicies in B1 (reference Tables 4, 5, and 6)**

```r
> summary(a)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
  9.39   64.95   81.40   90.87  105.60  187.10    2.00
> summary(b)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
 26.51   41.52   58.57   82.94  107.80  216.20    2.00
```
> summary(c)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
34.00   70.82  109.40  114.00  145.30  234.90    3.00

> summary(d)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
26.51   38.00   53.72   59.52   65.11  123.50    4.00

> summary(e)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
34.00   65.12  101.10  100.60  134.50  173.40    4.00

> summary(f)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
23.09   31.29   39.48   44.70   48.41   88.85    5.00

> summary(g)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
34.00   42.81   65.12   66.19  87.93  101.10    8.00

> summary(h)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
23.09   24.16   33.67   32.74  40.39   42.40    8.00

> summary(i)
Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
32.38   36.88   38.55   38.51  40.18   44.57    9.00

**B11. R code for all 72 Hour Forecast Error Box Plots (reference Fig. 11)**

```r
> boxplot(a,b,c,xlab="72-hr Forecast",ylab="Error in km")
> title("Hurricane Rita:72-hr Forecasts")
```

**B12. R code for all 48 Hour Forecast Error Box Plots (reference Fig. 12)**

```r
> boxplot(d,e,f,xlab="48-hr Forecast",ylab="Error in km")
> title("Hurricane Rita:48-hr Forecasts")
```

**B13. R code for all 24 Hour Forecast Error Box Plots (reference Fig. 13)**

```r
> boxplot(g,h,i,xlab="24-hr Forecast",ylab="Error in km")
> title("Hurricane Rita:24-hr Forecasts")
```

**B14. R code for all 72 Hour Least Error Forecasts Box Plots (reference Fig. 14)**

```r
> boxplot(c,f,i,xlab="72,48,& 24-hr Final Forecasts",ylab="Error in km",col=(c("gold","red","green")))
> title("Hurricane Rita:Comparisons of Landfall Forecasts with Least Error")
```

c. **Linear Correlation**

**C1. R code for Linear Correlation comparing all forecasts for Hurricane Katrina and Hurricane Rita (reference Fig. 15)**

```r
> data=read.table("clipboard",header=T)
> dist=data$dist
> time=data$time
```
> plot(time~dist)
> plot(dist~time)
> data.fit=lm(dist~time)
> summary(data.fit)

Call:
   lm(formula = dist ~ time)

Residuals:
   1     2     3
  0.8  -1.6   0.8

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 14.800000  2.993333   4.944 0.1270
   time     -1.541670  0.057740 -26.702 0.0238 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.96 on 1 degrees of freedom
Multiple R-squared: 0.9986,  Adjusted R-squared: 0.9972
F-statistic:  713 on 1 and 1 DF,  p-value: 0.02383

> abline(14.8,-1.54167,col="red")
IV. References

GARP Modeling Package

