Tracking Hurricane Katrina with Vorticity and Okubo Weiss Parameter

Final Project

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1 Introduction

Hurricane Katrina, tropical cyclone that struck the southeastern United States in late August 2005. The hurricane and its aftermath claimed more than 1,800 lives, and it ranked as the costliest natural disaster in U.S. history. Hurricane Katrina surfaced on August 23, 2005, as a tropical depression over the Bahamas. After two days, Tropical Storm Katrina made land fall to Florida as a category 1 hurricane. Then, on August 27 Katrina strengthened to a category 3 hurricane and covered nearly the entire Gulf of Mexico. On the morning of August 29, the storm made landfall as a category 4 hurricane at Louisiana and it caused severe flooding damage to Mississippi, New Orleans, and Louisiana. In this study, Hurricane Katrina tracked with vorticity and Okubo Wiess parameter too see that can Okubo Weiss parameter be used in place of vorticity.

Vorticity is a clockwise or counterclockwise spin in the troposphere. Vorticity caused by a change in wind direction or wind speed with height is termed horizontal vorticity (the spin is in relation to a horizontal axis). Horizontal vorticity is most important in the planetary boundary layer (low-levels of atmosphere). It is mathematically defined as the curl of velocity:

$$\omega = \vec{\nabla} x \vec{V}$$

Shear is a change in wind speed over some horizontal distance. Curvature is a change in wind direction over some horizontal distance. This change will result in either a counter-clockwise or clockwise curvature. When relative vorticity is positive, curvature is counter-clockwise and when it is negative, curvature is clockwise. Relative vorticity considers shear and curvature vorticity:

$$\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

The Okubo Weiss parameter (W) is the difference between vorticity and strain and an eddy tracking tool used in oceanography. It is consist of the normal component of strain ($S_n^2 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$), the shear component of strain ($S_s^2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$), and vorticity ($\omega^2$):

$$W = S_n^2 + S_s^2 - \omega^2$$

The Okubo Wiess parameter increases in negative values as getting closer to the core of the eddy and the outside ring of the core of the eddy has large positive values [1]. The flow are separated into vorticity-dominated and deformation-dominated regions by means of the Okubo Wiess parameter. The core region of the eddy is dominated by vorticity and the outer ring is dominated by deformation [2]. The Okubo Weiss was discovered by Claude Basdevant and Thierry Philipovitch. The vorticity gradient field develops in connection with the primary straining flow-velocity gradient field. This is the main assumption of the Okubo Weiss creterion [3].
As it is seen in many cases, the Okubo Wiess parameter is used for eddies in ocean. In this study, vorticity and the Okubo Weiss paramater are calculated in 850 hPa to explore the parameter is suitable for atmosphere.

2 Data and Methods

ECMWF Era-Interim data was used for u and v component of wind. Also, storms datasets (Atlantic hurricane database (HURDAT2) 1851-2016) of dplyr package of R was used for tracking data and it is from National Hurricane Center (NHC) National Oceanic and Atmospheric Administration (NOAA).
Firstly, all libraries were introduced and u and v components of wind were read by library ncdf4. Also, longitude, latitude were read in a for loop since 35 time steps were required to track the hurricane.

```
library(ncdf4) # For reading the netCDF file
library(RColorBrewer) # For color palttes
library(fields) # For plotting
library(maps) # For basemaps
library(animation) # For making gif
library(dplyr) # For using storms dataset
library(ggmap)  # For maps like library maps

for (i in seq(90,124,1)) {

fileobj<-nc_open("850_56_42_124.nc")
u<-ncvar_get(fileobj,"u")
v<-ncvar_get(fileobj,"v")
```

Secondly, vorticity and Okubo Wiess parameter were calculated using forward difference approximation:

$$f(x_i) = \frac{f(x_{i+1}) - f(x_i)}{dx}$$

While calculating, v with respect to x means change between longitudes and u with respect to y means change in latitude. So, after calculating, the dimensions of($\frac{\partial v}{\partial x}$) and ($\frac{\partial u}{\partial y}$) were off since the data includes different number of latitudes and longitudes. The last row/column were added using cbind and rbind functions to the end so that dimensions match. Now, ($\frac{\partial u}{\partial y}$) can be subtracted from ($\frac{\partial v}{\partial x}$).

```
dx=dy=80000 # resolution 80km = 80000m

dudy = (uvel[,2:42] - uvel[,1:41])/dy
dvdx = (vvel[2:56,] - vvel[1:55,])/dx

y = (array(1, dim = c(56,1)))
yy = y*dudy[,41]

x = (array(1, dim = c(1,42)))
xx = x*(t(dvdx[55,]))

dudy = cbind(dudy,yy)
dvdx = rbind(dvdx,xx)

vort = dvdx-dudy
```

($\frac{\partial u}{\partial x}$) and ($\frac{\partial v}{\partial y}$) were calculated as vorticity was calculated for the Okuba Wiess's S_n^2 component.
Thirdly, they were visualised in the same way. library maps was used for base map and library fields was used for plotting. Time difference between t and t+1 is 6 hours and from August 23 to August 31, 35 frames were saved for vorticity and another 35 frames saved for the Okuba Weiss parameter as jpeg. After saving the frames, two gif files were made using library animation one for vorticity and one for the Okubo Weiss. Now, Hurricane Katrina track can be watched from gif files.

```
par(mar=c(0.1,0.1,0.1,0.1))

map(database="world", resolution = 0)

jpeg(file=paste("Vorticity_", i, ".jpeg", sep = ""),width=640,height=480)

mycol = c(rev(brewer.pal(9,"Reds")), brewer.pal(8,"Blues"))

mybreaks= c(seq(-0.0001,0.0006,length.out = 18))

Longitude =Longitude-360 ;   Latitude = rev(Latitude)

image.plot(Longitude,Latitude,vort, breaks = mybreaks , col = mycol,horizontal = T,
           legend.lab = "Vorticity (1/s)")

title(main = paste("Vorticity  " ,dtime[i]) , xlab = "Longitude", ylab = "Latitude")
```

```
map(database = "world", resolution = 0, add = T)
dev.off()

ani.options(interval = 0.25) # frame delay

files = sprintf(paste("Vorticity_%i.jpeg"), 90:124)

im.convert(files =files, output = "Vorticity.gif") # jpegs to gif
```

Finally, to check the accuracy of the calculations, library dplyr's storms dataset is used for tracking data. Name, year, month, day, hour, category, latitude, and longitude variables were selected and selected varibles were held by dplyr's pipe (% > %) for mutate function and new time variable were created with mutate function in hurricane variable. Class of the storms dataset is tibble so, hurricane variable is a tibble. To rescue the variables from tibble's factors and levels, latitude, longitude, and category variables were extracted with pull function and turned in to data frame. Especially, category variable firstly turned into character, secondly numeric, lastly data frame since it holds the category data which will be used for plotting functions as input. Then, get_map function created base map. Aesthetics were generated with aes function and category data visualises with $geom_points$ for drawing data points on the map and $geom_path$ for drawing Hurricane Katrina track line. Also, this plot was saved as jpeg.

```
lat <- hurricane[6998:7029,] %>% pull(lat) ; Latitude =as.data.frame(lat)
lon <- hurricane[6998:7029,] %>% pull(long) ; Longitude= as.data.frame(lon)
category <- hurricane[6998:7029,] %>% pull(category)

Hurricane_Category =as.data.frame(as.numeric(as.character(category)))

katrina = data.frame(Latitude,Longitude,Hurricane_Category)

jpeg(file=paste("Track" ,".jpeg", sep = ""),width=1080,height=720)

map = get_map(location = c(lon = -95.3632715, lat = 29.7632836), zoom = 4 ,
scale = "auto")

hurricane_category <- ggmap(map) +
  ggtitle(paste("                           Hurricane Katrina Track between",
                  katrina_time[1],"and",katrina_time[32] ,sep = " ")) +
  geom_point(aes(x=Longitude, y=Latitude, size= Hurricane_Category)
             ,data = katrina, alpha= 0.5, color ="darkred") +
  geom_path(aes(x=Longitude, y=Latitude) ,data = Hurricane_Category, alpha=1)

hurricane_category

dev.off()
```

3 Results

In this section, calculated vorticity and the Okubo Weiss will be compared and be checked for accuracy with NOAA's hurricane tracking data (storms dataset).
In August 25, Katrina made land fall to Florida as a category 1 hurricane, as it seen in Figure 1 and Figure 2. The Okubo Wiess parameter has negative values on the core of the hurricane and the outer ring has positive values over Florida. Vorticity increases as getting closer to the core of the hurricane. On August 27 Katrina strengthened to a category 3 hurricane, as it seen in Figure 3 and Figure 4.

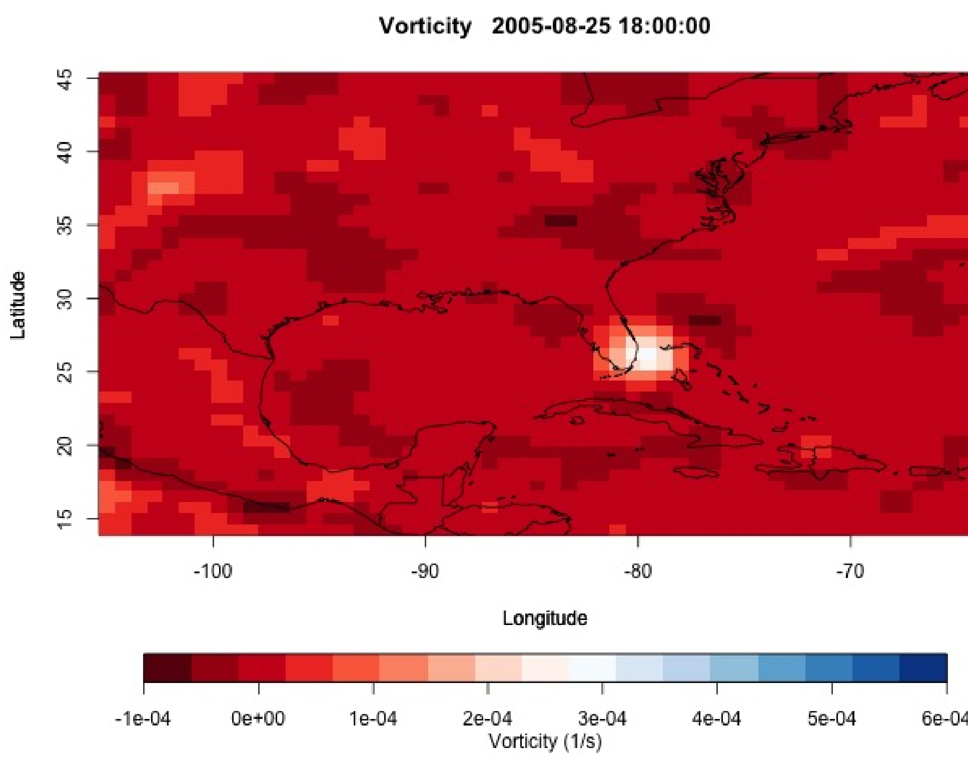

Figure 1: Vorticity map of category 1 hurricane over Florida.

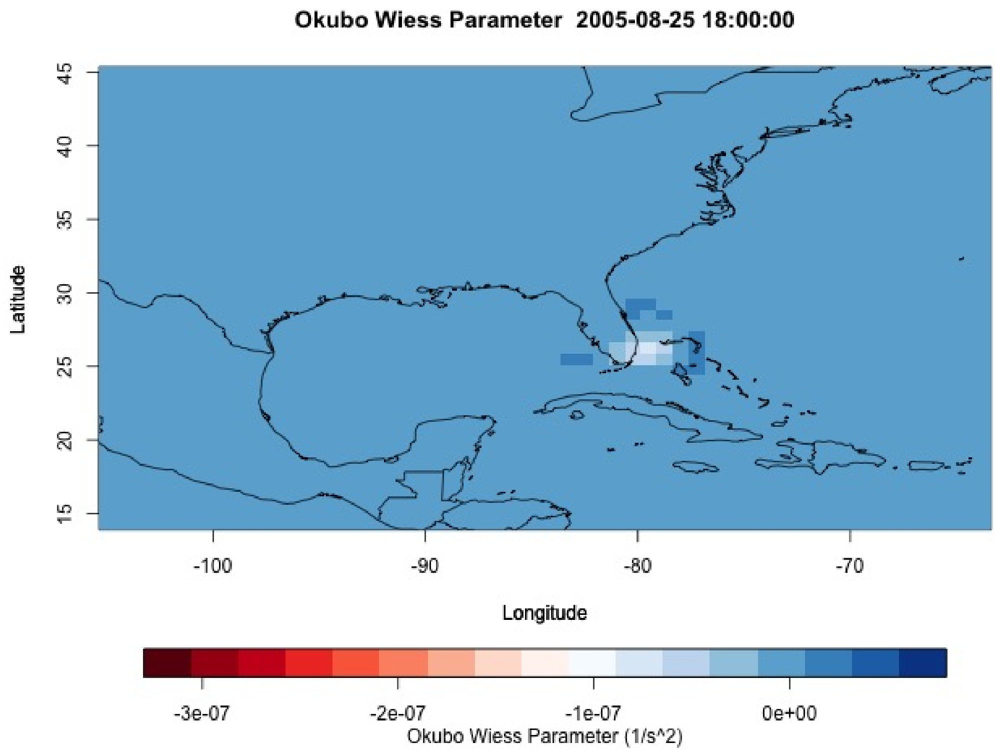

Figure 2: Okubo Weiss Parameter map of category 1 hurricane over Florida.

The core of the hurricane has larger negative values than August 25 and the outer ring has positive values in Figure 4. Also, the location of hurricanes are same in Figure 3 and Figure 4. The outer ring is dominated by strain and the Okubo Wiess parameter can catch the strain on the atmosphere.
On the morning of August 29, the storm made landfall as a category 4 hurricane at Louisiana, as it is seen in Figure 5 and Figure 6. Hurricane strengthened and covered very large area in category 4. Again, locations of Hurricane Karina are still matching in Figure 5 and Figure 6.On August 30 at midnight , Hurricane Katrina moved along to the interior land as category 1, as it is seen in Figure 7 and Figure 8. At this stage, the Okubo Weiss parameter are still following vorticity, so locations of Hurricane is same in both plot. After this stage, Hurricane Katrina moved along till noon and than disappeared slowly.

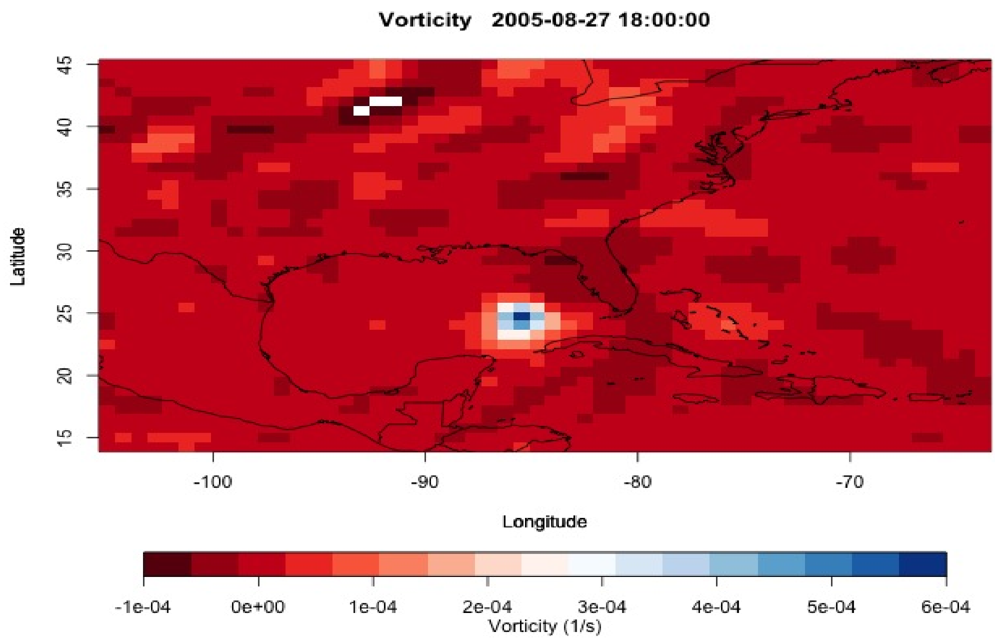

Figure 3: Vorticity map of category 3 hurricane over Gulf of Mexico.

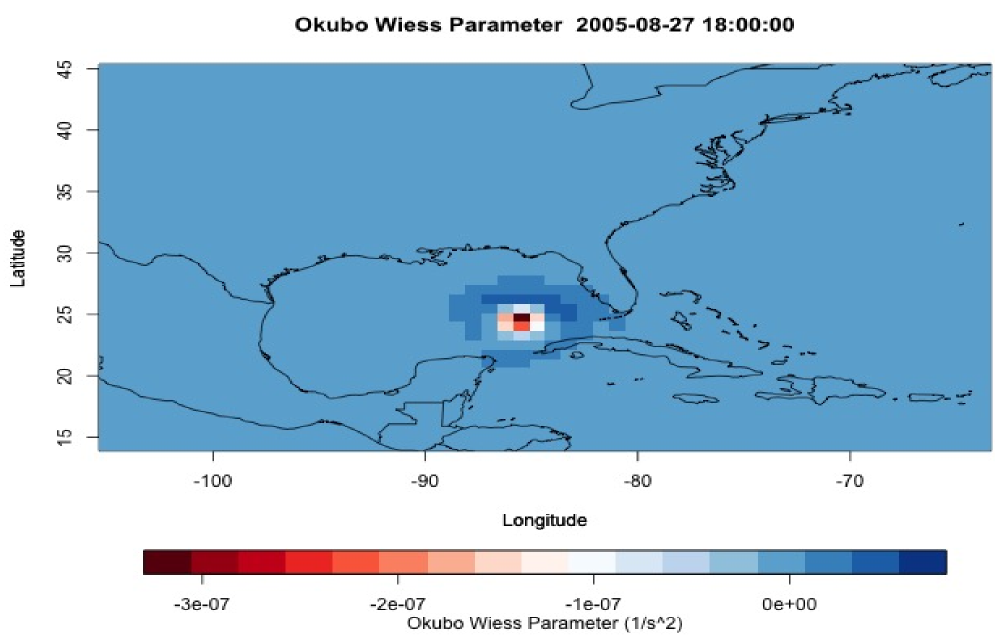

Figure 4: Okubo Weiss Parameter map of category 3 hurricane over Gulf of Mexico.

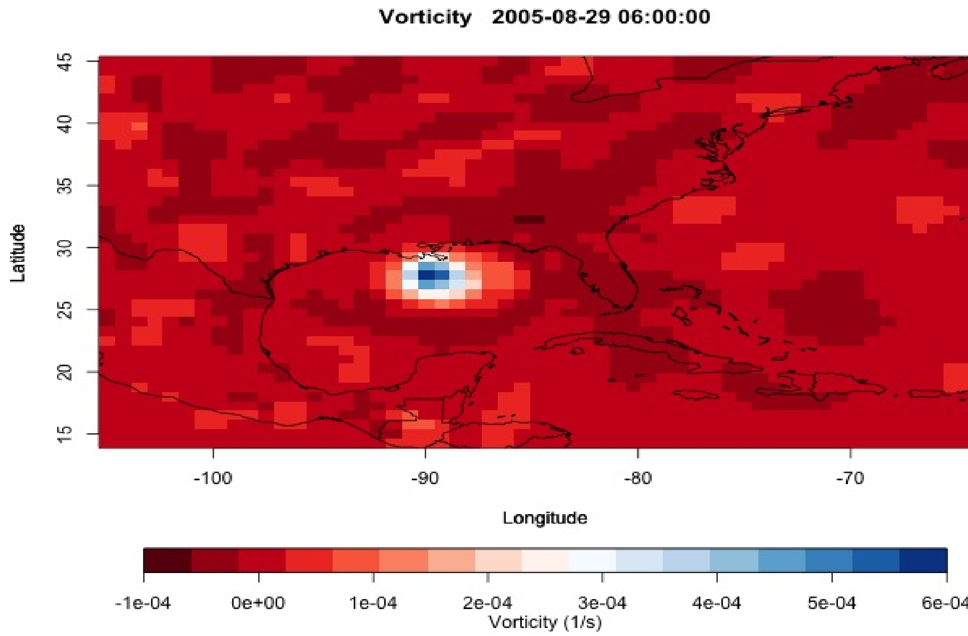

Figure 5: Vorticity map of category 4 hurricane over Louisiana.

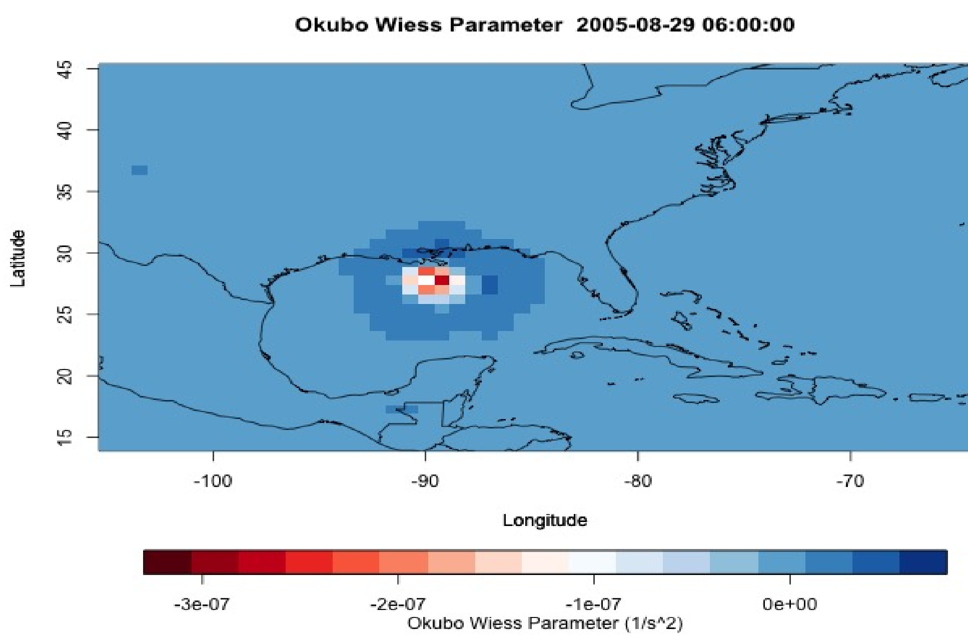

Figure 6: Okubo Weiss Parameter map of category 4 hurricane over Louisiana.

To check the accuracy of the calculations, Figure 9 were plotted using Atlantic hurricane database (HURDAT2). As it is seen from Figure 1 to Figure 8, the location and the magnitude of Hurricane Katrina meet Figure 9.

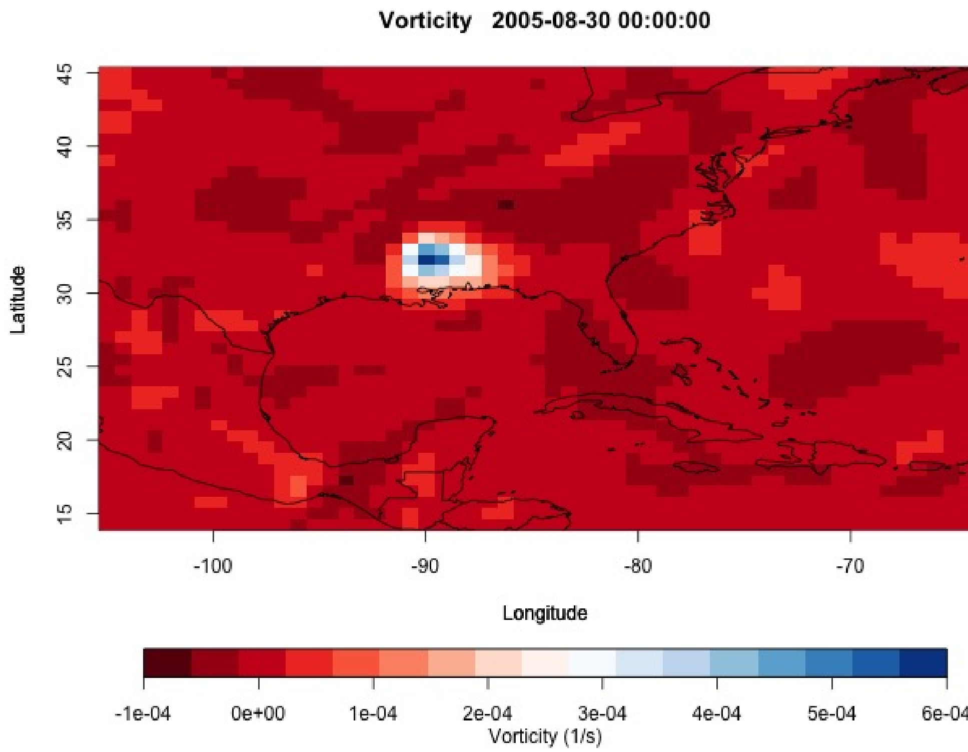

Figure 7: Vorticity map of category 1 hurricane over interior land.

In conclusion, the Okubo Weiss parameter followed perfectly the vorticity in all stages of the hurricane. All locations of the hurricane in Okubo Weiss Parameter map are the same with vorticity maps. In the light of this information the Okubo Weiss parameter can be used instead of vorticity in the atmosphere without any problem.

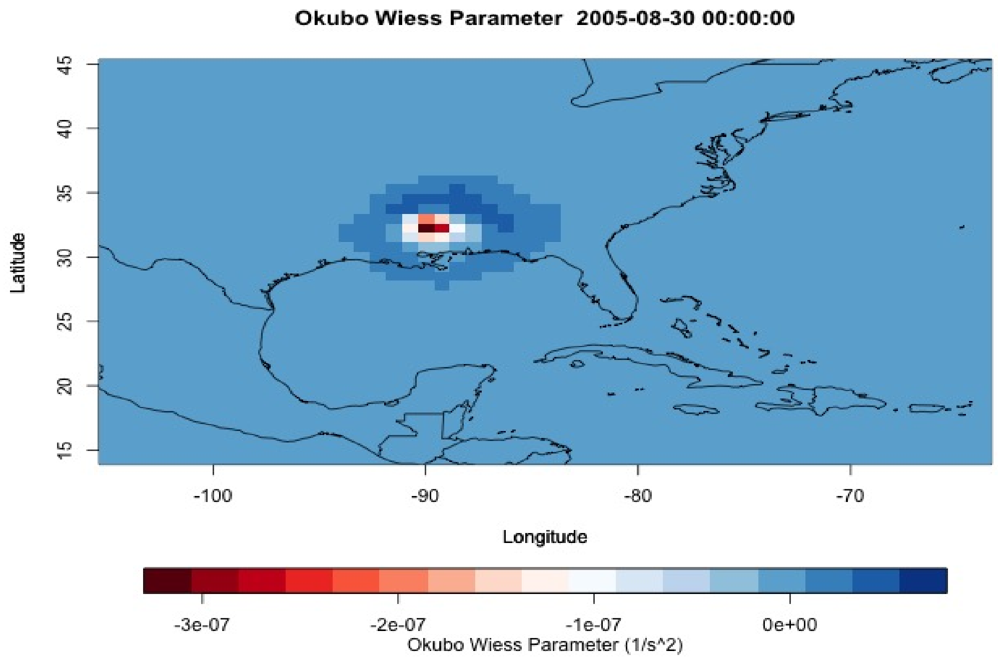

Figure 8: Okubo Weiss Parameter map of category 1 hurricane over interior land.

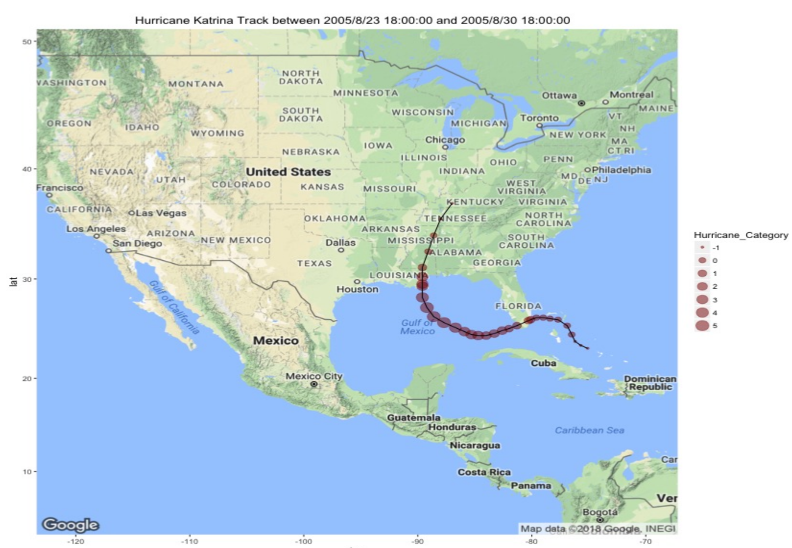

Figure 9: Hurricane Katrina Track

References

[1] A. C.-T. Hsu. North atlantic mesoscale eddy detection and marine species distribution. manuscript, 2010.

[2] J. Isern-Fontanet, J. Font, E. Garcia-Ladona, M. Emelianov, C. Millot, and I. Taupier-Letage. Spatial structure of anticyclonic eddies in the algerian basin (mediterranean sea) analyzed using the okubo-weiss parameter. manuscript, 2004.

[3] B. K. Shivamoggi, G. J. F. van Heijst, and L. P. J. Kamp. Spatial structure of anticyclonic eddies in the algerian basin (mediterranean sea) analyzed using the okubo-weiss parameter. manuscript, 2011.