Laboratory Experiments on Tropical Cyclone Dynamics

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1. Introduction

1.1. Background

Tropical Cyclones originate over tropical oceans and are driven principally by heat transfer from the ocean (Emanuel 1995). The word “cyclone” on its own is used to denote any center of low pressure towards which, by the well known Coriolis effect, surface winds, spiral inwards cyclonically (Lighthill 1998). The maximum wind speed in a tropical cyclone is quite large and is greater than 32 m/s (Emanuel this lecture). Therefore, a tropical cyclone is well known as an outstanding natural hazard (for example, Hurricane Katrina in 2008). In this work, we investigate impacts of the following conditions on the strength of a tropical cyclone using a simple hurricane model.

- The sea and land surface conditions (Section 2)
- SST (Section 3)
- Oceanic environmental parameters (Section 4)

1.2. Model

Our model is based on a simple hurricane model developed by Emanuel (1995). This model is axisymmetric and divided into the two layers. One is an Ekman layer near the surface where the atmosphere loses the energy due to the surface drag and obtains entropy from the sea surface. This entropy flux from the surface is turned off after the hurricane makes landfall. The other is the troposphere, where angular momentum is conserved along the movement of a parcel and the gradient wind balance is achieved. Potential radius, R, is defined as below,

$$\frac{1}{2} fR^2 = rV + \frac{1}{2} fV^2, \tag{1}$$

where r, V and f are the distance from the center of a hurricane, the azimuthal wind and the

Coriolis parameter, respectively. R corresponds one-to-one with absolute angular momentum and increases monotonically in the radial direction. Therefore, we use potential radius as the horizontal coordinate in the model to simplify the basic equations and to achieve high horizontal resolution near the eye wall.

2. Effects of the sea and land surface condition on the strength of a hurricane

Fig. 1A shows the best track of Hurricane Dolly which occurred in 2008. Dolly made landfall around noon on July 23rd. As shown in Fig. 1B, Dolly dissipated rapidly just after landfall. Thus, it is possible that the surface condition affected the growth and decay of the hurricane. In this study, we investigate effects of the sea and land surface conditions on the strength of a hurricane using a simple hurricane model.

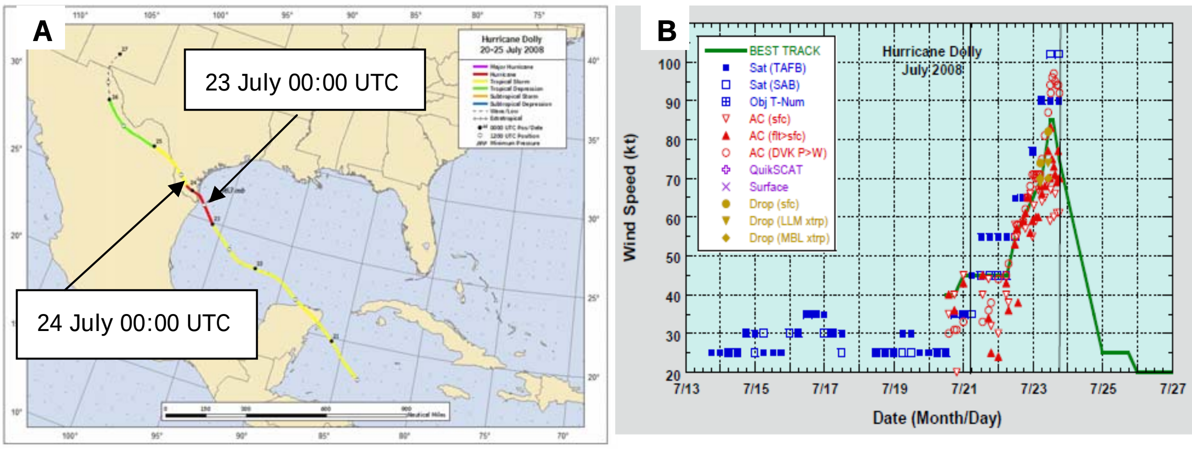

Figure 1. (A)The best track of Hurricane Dolly. (B) A time-series of the observed wind speed at the top of the boundary layer in Dolly (http://www.nhc.noaa.gov/).

2.1. Impacts of landfall

Fig. 2 shows a time-series of the maximum wind speed inside hurricanes simulated by our model. A hurricane which does not make landfall does not dissipate after maturation. The other hurricane which makes landfall on the 20th day dissipates rapidly after landfall because the surface entropy flux is turned off after the landfall, aided by the successive energy output due to the surface drag and radiative cooling. Note that the surface drag, which can contribute to the dissipation of a hurricane, becomes large at the same time. Therefore, it cannot be concluded straightforwardly that the entropy flux from the sea surface is really critical for the maintenance of a hurricane.

2.2. The surface entropy flux VS the surface drag

Fig. 3 shows time-series of the maximum wind speed inside the simulated hurricanes in the three cases where the surface drag coefficients of the land are modified. These three cases correspond to the different topography: plain, hill and mountains. As shown in Fig. 3, the differences of the maximum wind speed among the three cases are very small compared with the difference between the control run and the plain experiment shown in Fig. 2. Therefore, the surface entropy flux from the sea is the most important for the maintenance of a hurricane, and its absence is most important for its dissipation after landfall.

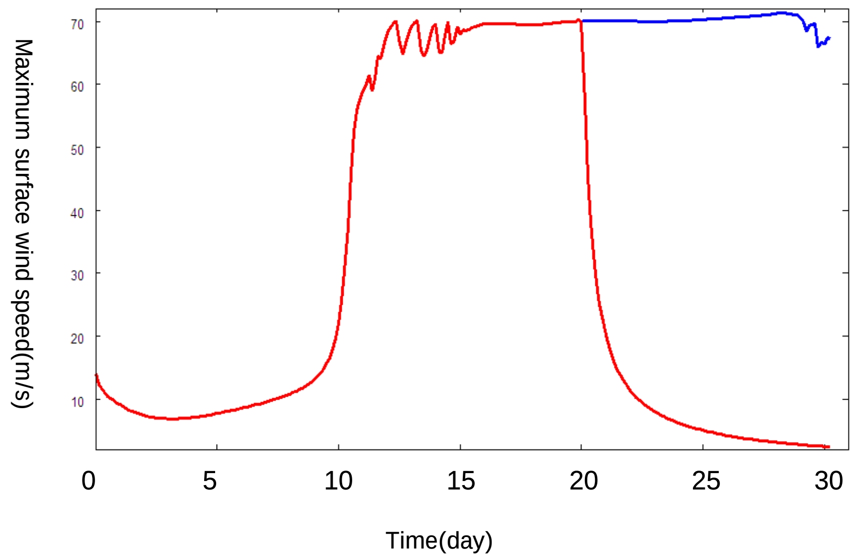

Figure 2. Time-series of the maximum surface wind speed in hurricanes simulated by our model. (blue) The Control run where a hurricane doesn't make landfall. (red) The plain experiment where a hurricane makes landfall over plain land on 20th day. The red and blue lines indicate exactly the same values until the 20th day.

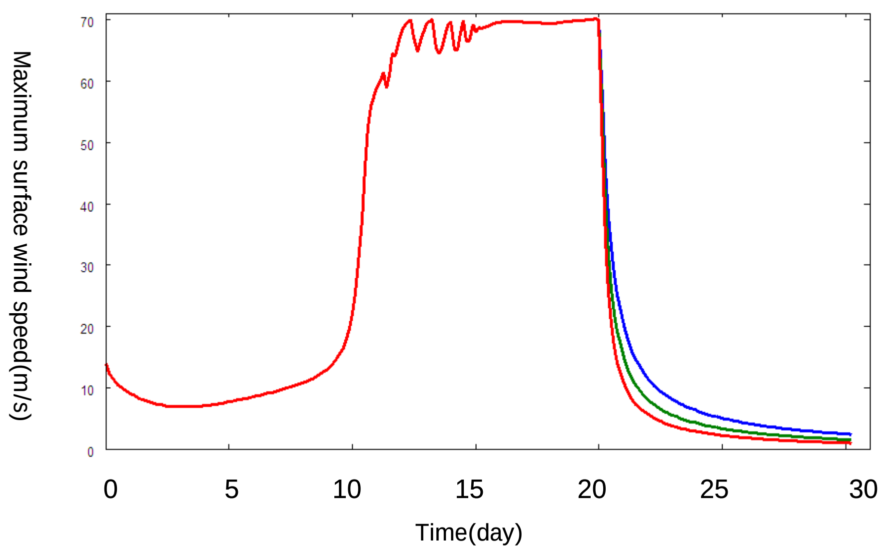

Figure 3. Time-series of the maximum surface wind speed inside the simulated hurricanes. Red, green and blue lines indicate the three different cases where the surface drag coefficients are modified. (blue) The plain experiment (small drag coefficient). (green) The hill experiment (middle drag coefficient). (red) The mountain experiment (large drag coefficient). The surface drag coefficients used in these three cases are larger than that used in the control run shown in Fig. 2. The simulated hurricanes make landfall on the 20th day in all cases.

1. Effects of Sea Surface Temperature (SST) on Tropical Cyclone Characteristics

A test of the sensitivity of typhoon characteristics to sea surface temperature was conducted using a simple hurricane model. Sensitivity tests were used to study the effect of SST changes on the maximum surface wind speed, maximum convective updraft mass flux, surface pressure and the surface azimuthal velocity of a tropical cyclone.

Note that for the simulation model, the predetermined value for the SST is 27˚C which is known to be the minimum SST required for a tropical cyclone formation (as normal minimum SST required for a tropical cyclone lies between 26˚C to 28˚C). In the first run, SSTs with two unit degree difference were tested, including an SST fof29˚C. The model result showed an irregular change in the maximum surface wind speed for SST 29˚C. When SST is equal to 29˚C, the maximum surface wind speed increases abnormally and drastically, which is higher than normal standard (refer to Fig.4).

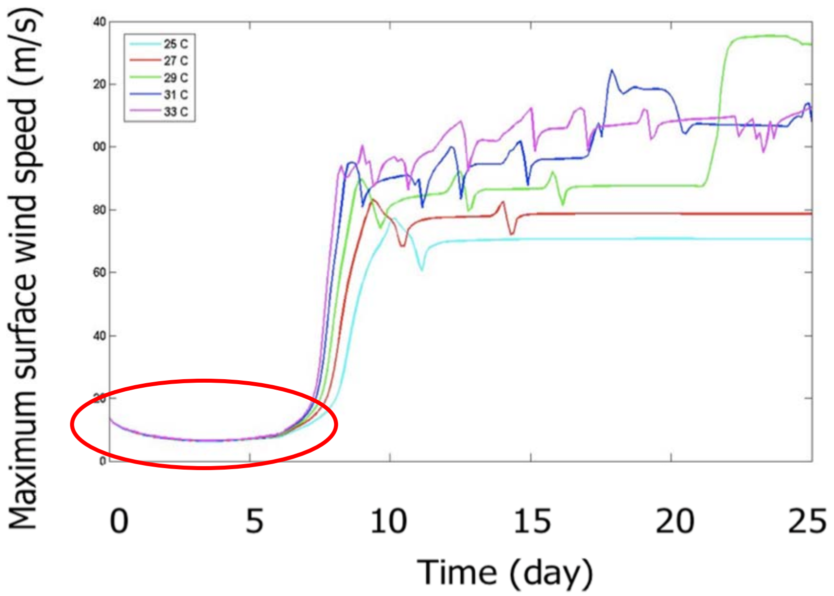

Figure 4. Time-series of the maximum surface wind speed in tropical cyclone on the first run. The default value is 27˚C (red) and the anomalous value is 29˚C (green).

1.1. Analyzing the Effect of the Change of SST on Surface Wind Speed and Convective Updraft

From the model result (Fig. 5A), higher SST values contribute to a stronger maximum surface wind speed. The encircled area in Fig. 5A shows that there is no change of the surface wind speed with SST variation for the first six days of the simulation. This is due to the fact that the ocean energy plays a more important role in the evaporation of the sea water which in turn provides the necessary condition (e.g. moisture in the air) before a tropical cyclone can start to develop. Starting from the sixth day of the model simulation, SST variations start to show more significant effect on the surface wind speed since the air is now saturated. As shown from Fig. 5A, the higher SST will result in a higher surface wind speed.

Fig. 5B shows the same scenario as Fig.5A for the first six days of the simulation, but showing the convective updraft mass flux. After the sixth day, the convective updraft increases with SST.

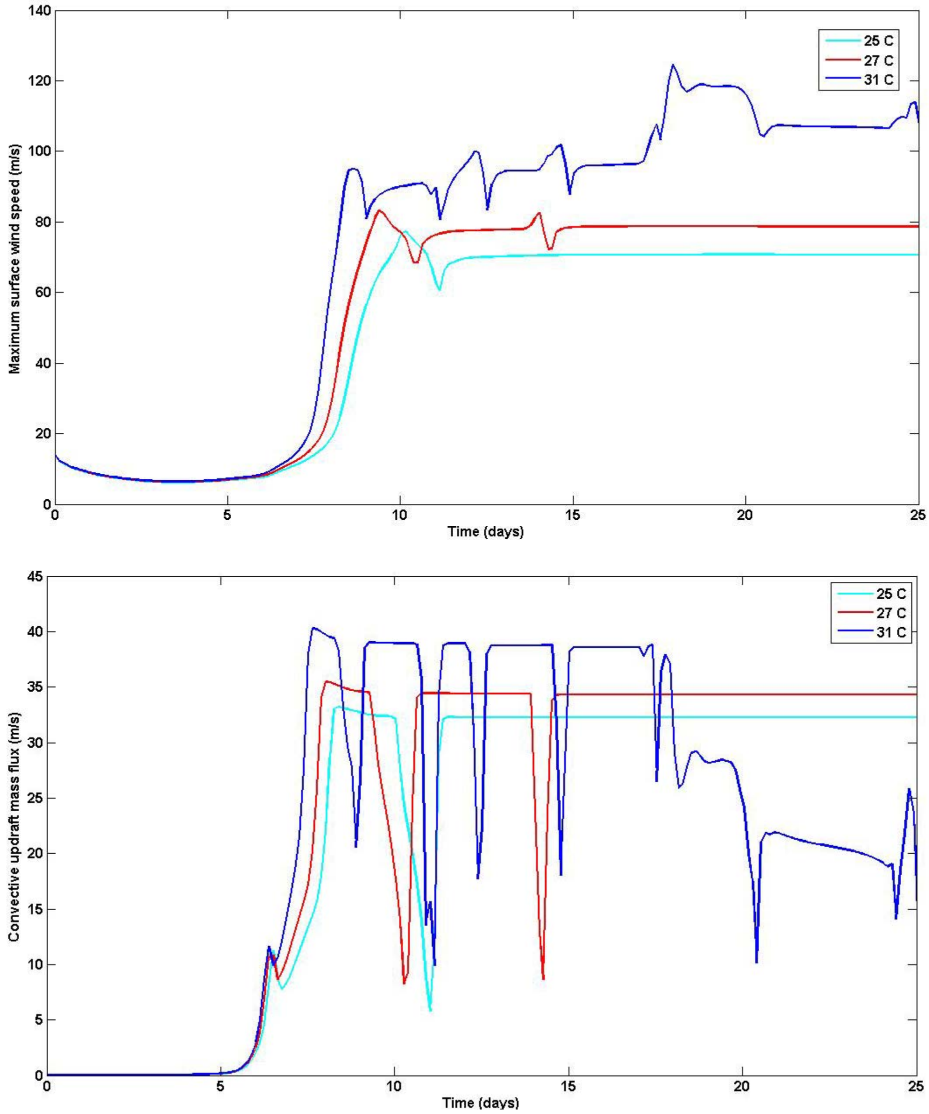

Figure 5. (A; Top)Time-series of the maximum surface wind speed in tropical cyclone on the final run. The default value is 27˚C (red), the lowest value set is 25˚C (cyan), and the highest value is 31˚C (blue). (B; Bottom)Time-series of the convective updraft mass flux in tropical cyclone on the final run.

Even though the simple model simulation on a tropical cyclone might not reflect reality, it still depicts the general pattern of tropical cyclone behaviors with respect to SST changes. In conclusion, from the model simulation, the surface azimuthal velocity, maximum surface wind speed and convective updraft of a tropical cyclone increased with increasing SST. The surface pressure, on the other hand, decreased with increasing SST.

1.2. Analyzing the Effect of the Change of SST on Azimuthal Velocity and Surface Pressure

Fig. 6A shows the increase in surface azimuthal velocity with SST. The surface azimuthal velocity is highest in the eyewall of the tropical cyclone. From Fig. 6A, the surface azimuthal velocity decreases as one goes further from the eyewall of the tropical cyclone. However, the surface pressure decreases with increasing SST, as shown in Fig. 6B.

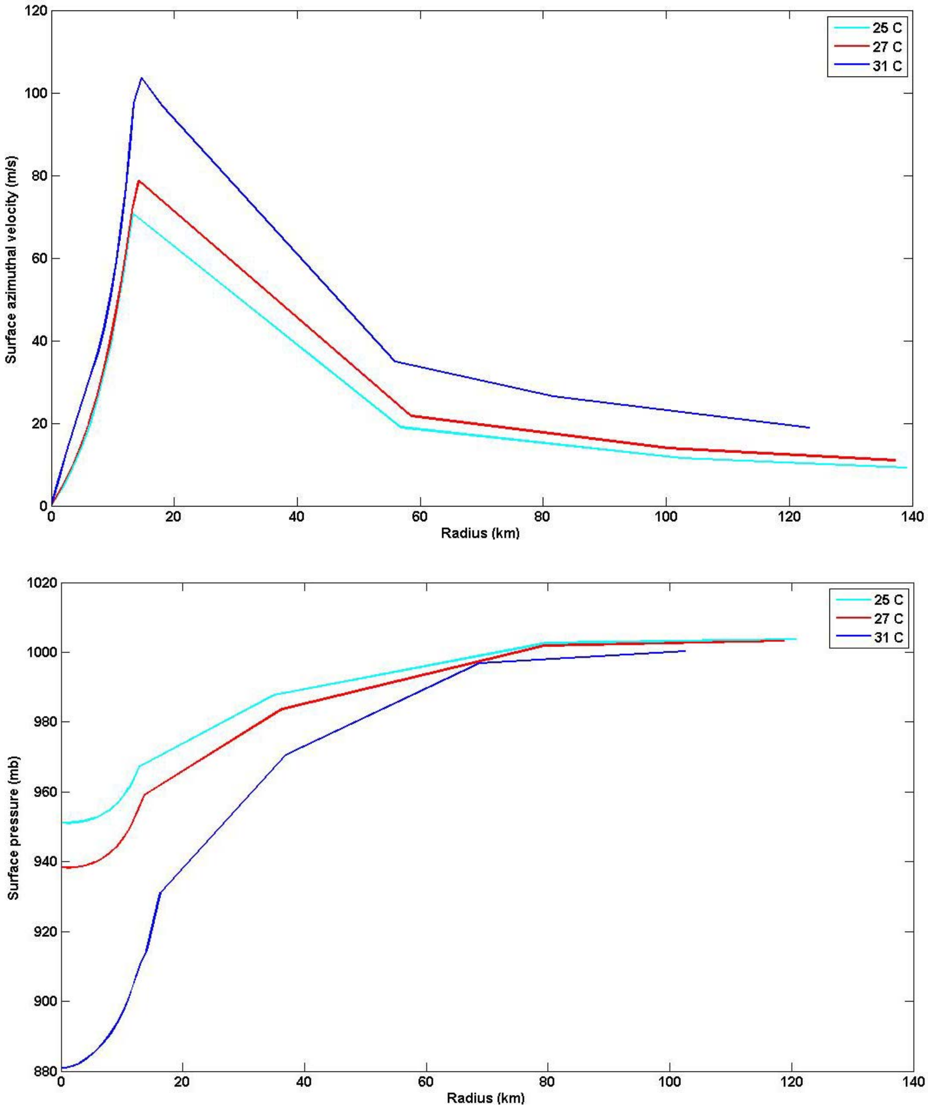

Figure 6. (A; Top) Radial-series of the surface azimuthal velocity in tropical cyclones on the final run. (B; Bottom) Radial-series of the surface pressure in tropical cyclones on the final run.

2. Oceanic Environmental Parameters

In this section, we investigate the effect of varying the parameters dealing with the interactions between the hurricane and the ocean.

2.1. Ocean mixing

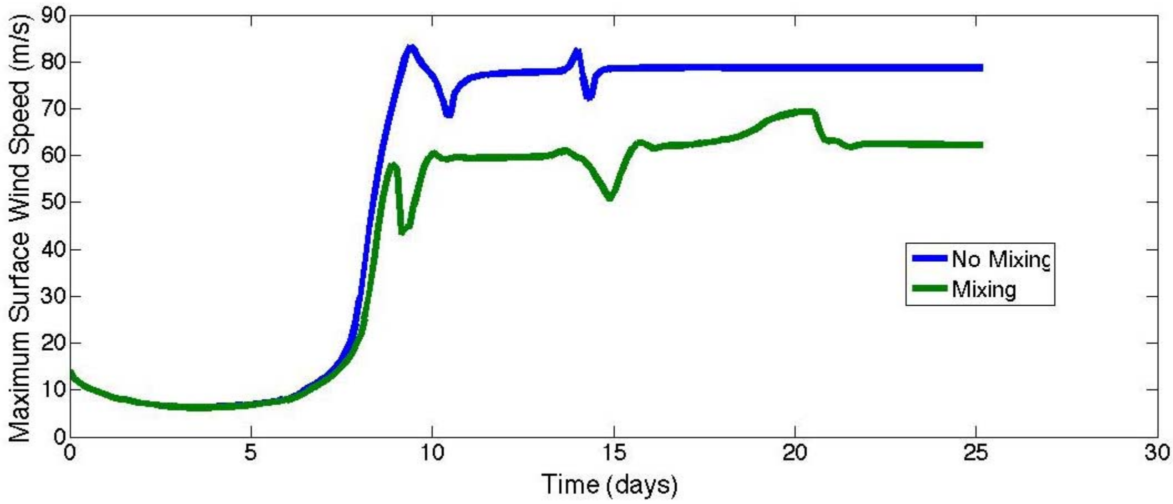

Figure 7. Ocean mixing generally decreases the maximum surface wind speed.

Figure 7 shows the effect of ocean mixing. Recall that in the hurricane model, we set the mixed layer depth equal to 30 m. Upon mixing, the cold water below mixes into the mixed layer, thereby causing a decrease in the Sea Surface Temperature (SST). The hurricane gets weaker because of lower entropy flux from the ocean as shown by the green line above. The blue line represents the result of running the simulation using the control values with fixed SST.

2.2. Peak ocean mixed layer depth anomaly in eddy

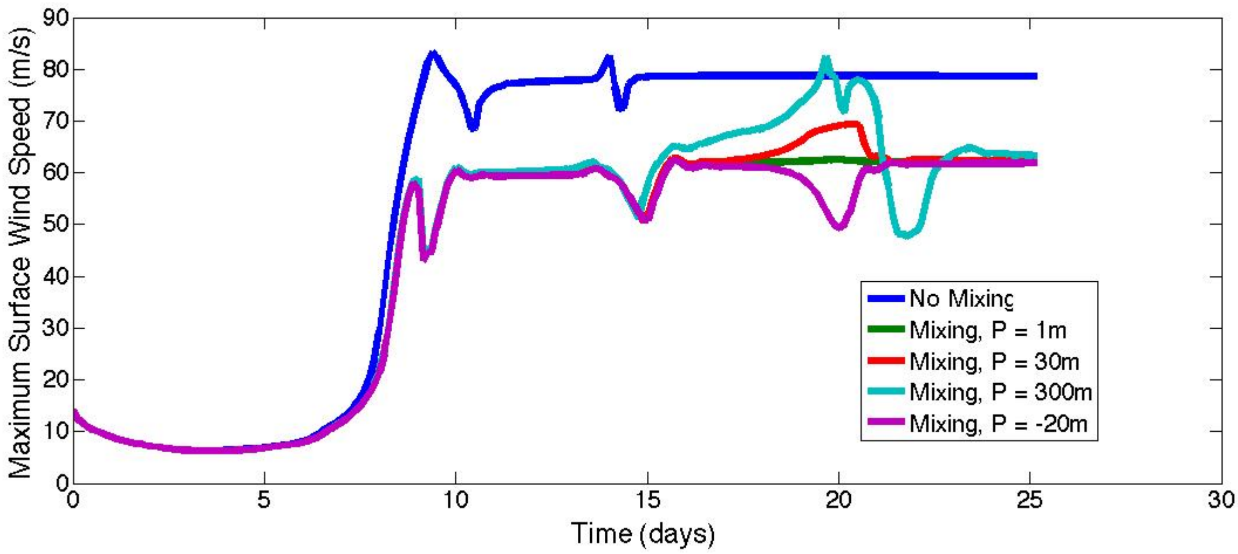

Figure 8. Positive ocean mixed layer depths show an increase in Maximum Surface Wind Speed (MSWS). for T = 20 days while negative values represent a decrease in MSWS.

We associate a peak ocean mixed layer that has a Gaussian distribution. For larger depths, the cold water from the peak layer cannot go up the surface of the ocean, causing a relatively small change in the SST, which leads to a stronger hurricane as observed for P = 30 and 300 m. However, if the hurricane becomes very strong, it will increase the rate of mixing, causing a smaller SST and a weaker hurricane as shown by the blue-green line. We also tried a negative value (note that it must no be bigger than the mixed layer) and the opposite is observed.

2.3. Effect of the time for storm center to reach center of ocean eddy

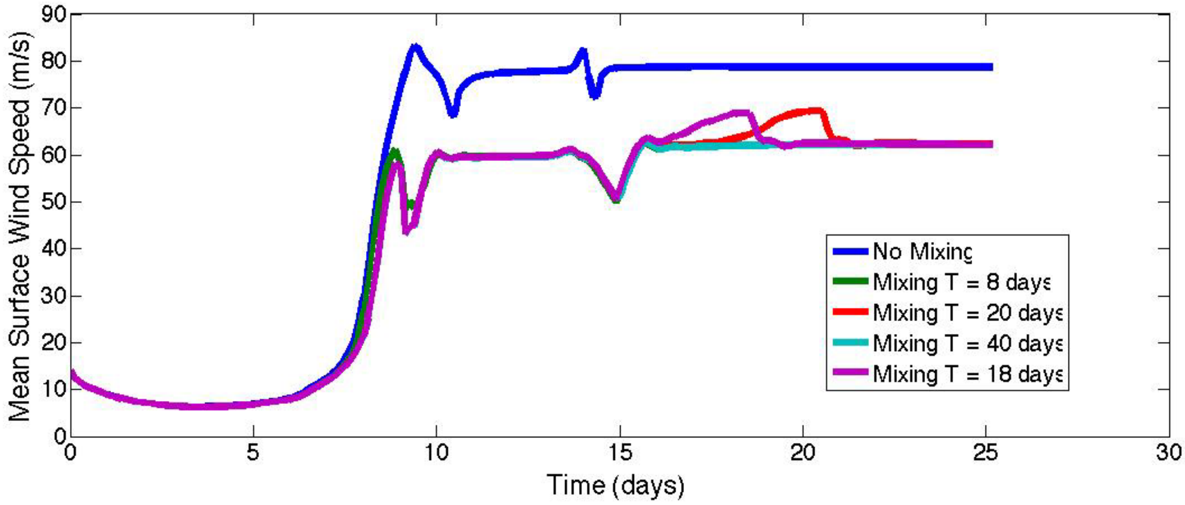

Figure 9. A noticeable deviation from the control mixing conditions are observed only for T = 18 and T = 20 days.

Both the T = 8 days (green line) and T = 40 days (blue green line) exhibit the same behavior. They represent a not-so-interesting case since the former represent the initial hurricane stage while the latter represents hurricane dissipation. However, for T = 18 and 20 days, as the hurricane reaches the peak depth of the ocean eddy, colder water cannot go up to the surface because the hurricane mixing cannot reach the bottom of the mixed layer. The hurricane then becomes stronger because of the relatively high SST. And as the hurricane becomes stronger, it is able to mix cold water into the mixed layer, thereby causing a decrease in the maximum surface wind speed at around T = 21 days.

2.4. Effect of the speed with which storm moves over ocean

For the V = 0 m/s case, the hurricane is stationary above an ocean eddy causing perfect mixing in the mixing layer. The hurricane then becomes weak with a constant maximum surface wind speed equal to 10 m/s, as shown in the green line in Figure 10. For higher velocity cases (V = 7 and 20 m/s) , the hurricane does not cause much ocean cooling, so it remains strong. The most interesting case is the case for V = 0.7 m/s, which shows an oscillation with an amplitude of around 20 m/s.

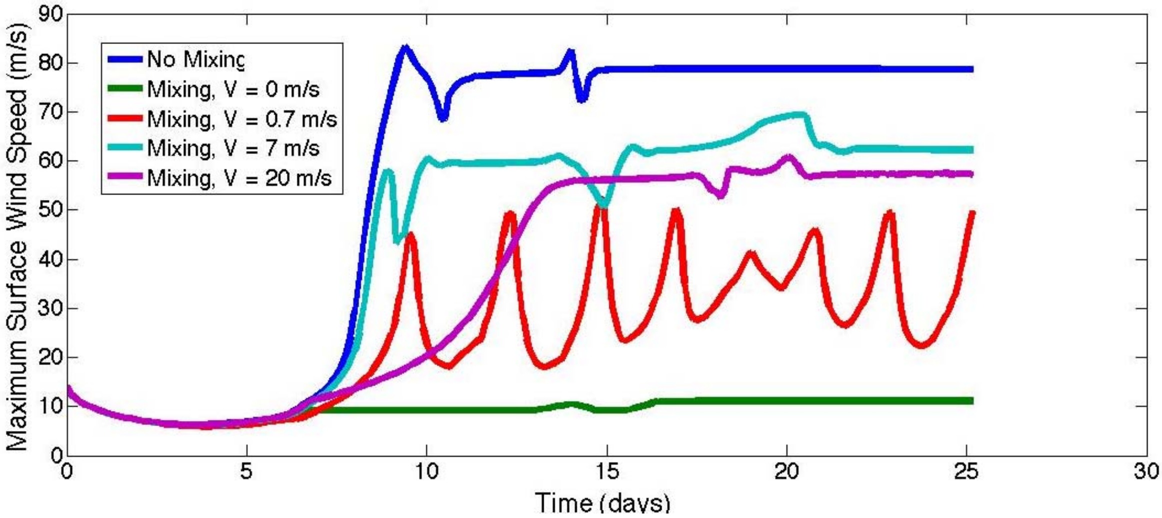

Figure 10. Drastic changes are observed as the speed is varied.

2.5. Effect of the radius of an ocean eddy

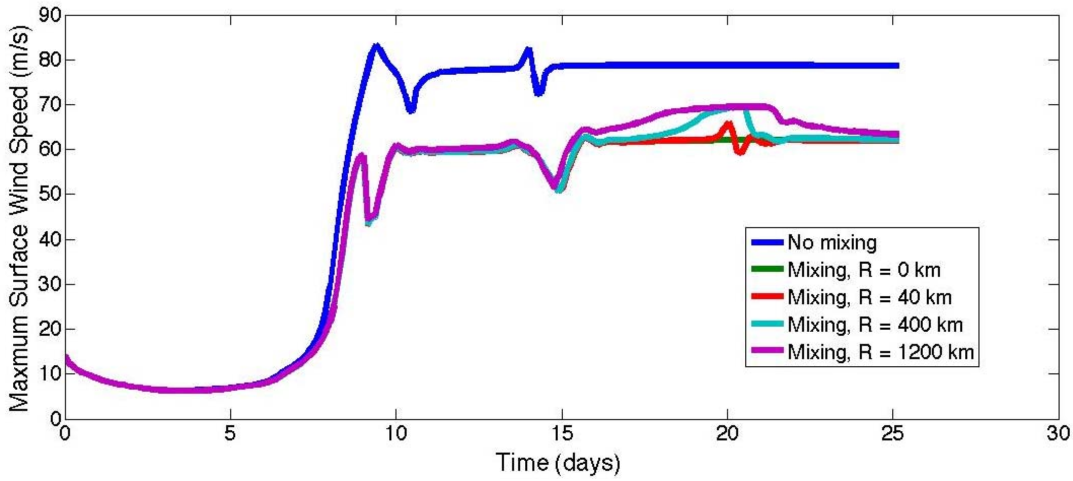

Figure 11. The larger the ocean eddy, the stronger the hurricane.

The larger the ocean eddy, the larger the heat flux from the ocean, resulting in stronger hurricanes (T = 15 to 25 days).