# A Highly Configurable Vortex Initialization Method for Tropical Cyclones

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# Motivation

- Data assimilation is the future. But, currently:
  - Observations (that are assimilated) are sparse.
  - Computationally expensive.
  - Complicated with a long learning curve.

- We wish to provide an alternative to existing bogus methods.
  - GFDL – axisymmetric spin-up. Asymmetries provided by asymmetric component of previous forecast at new initialization time. Too complex.
  - WRF – Idealized Rankine. Axisymmetric bogus data. Asymmetry provided by smooth environmental field. Too simple.

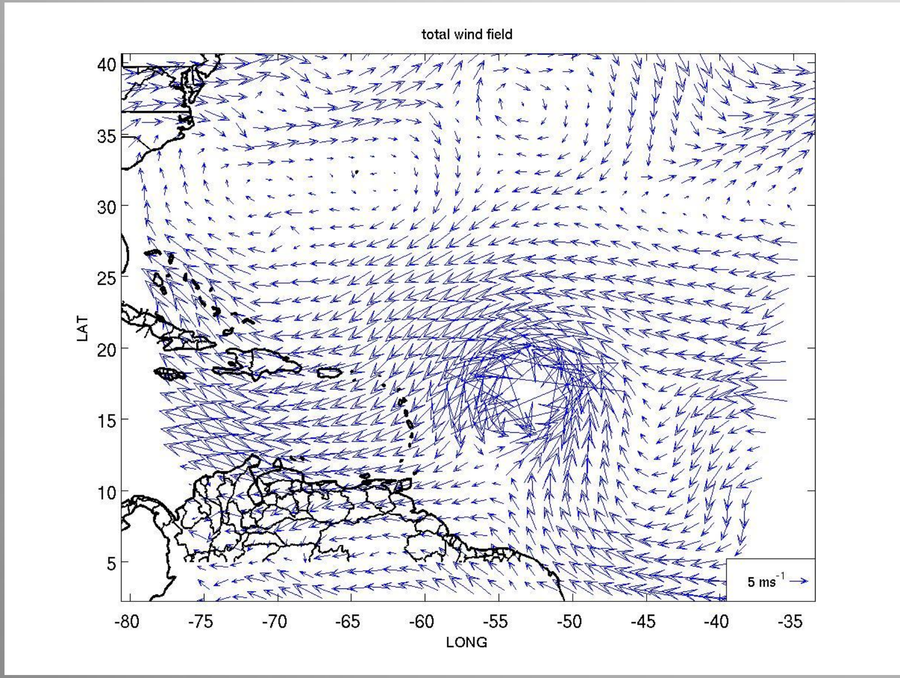
- New bogussing technique is:
  - Highly configurable to match any vortex shape.
  - Specify full three dimensional wind field to minimize adjustment period.

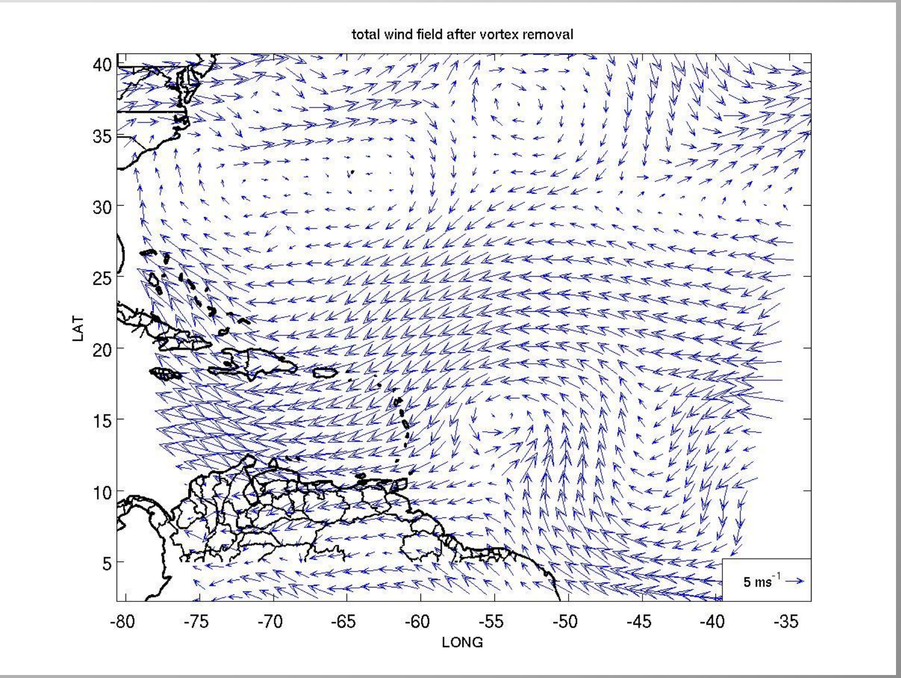
# Algorithm

- **Vortex Removal**
- Vortex Addition
  - Radial Structure:
    - Modified Rankine Vortex
    - Willoughby Vortex
  - Vertical Structure:
    - Boundary Layer
    - Free Atmosphere

# Algorithm – Vortex Removal

Largely follows Kurihara et al. (1995)



# Algorithm

- Vortex Removal
- **Vortex Addition**
  - **Radial Structure:**
    - **Modified Rankine Vortex**
    - **Willoughby Vortex**
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# Algorithm – Radial Structure

## Modified Rankine Vortex

$$V(r) = V_{max}\left(\frac{r}{R_{max}}\right) \qquad r < R_{max}$$

$$V(r) = V_{max}\left(\frac{R_{max}}{r}\right)^{\alpha} \qquad r > R_{max}$$

## Willoughby Vortex (Willoughby et al. 2006)

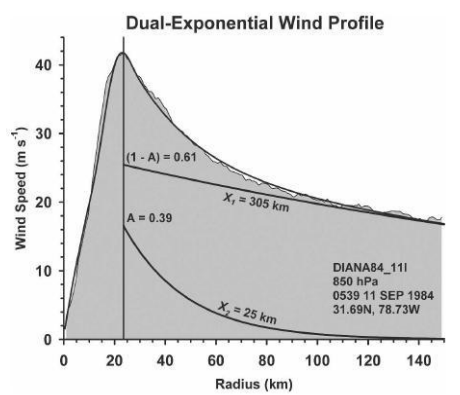


FIG. 2. A dual-exponential profile used to approximate the observed wind in Hurricane Diana on 11 Sep 1984. Here and subsequent shading indicates observed winds, and the darker curves indicate the fitted profiles.

$$V(r) = V_1 = V_{max}\left(\frac{r}{R_{max}}\right)^{n} \qquad r \le R_1$$

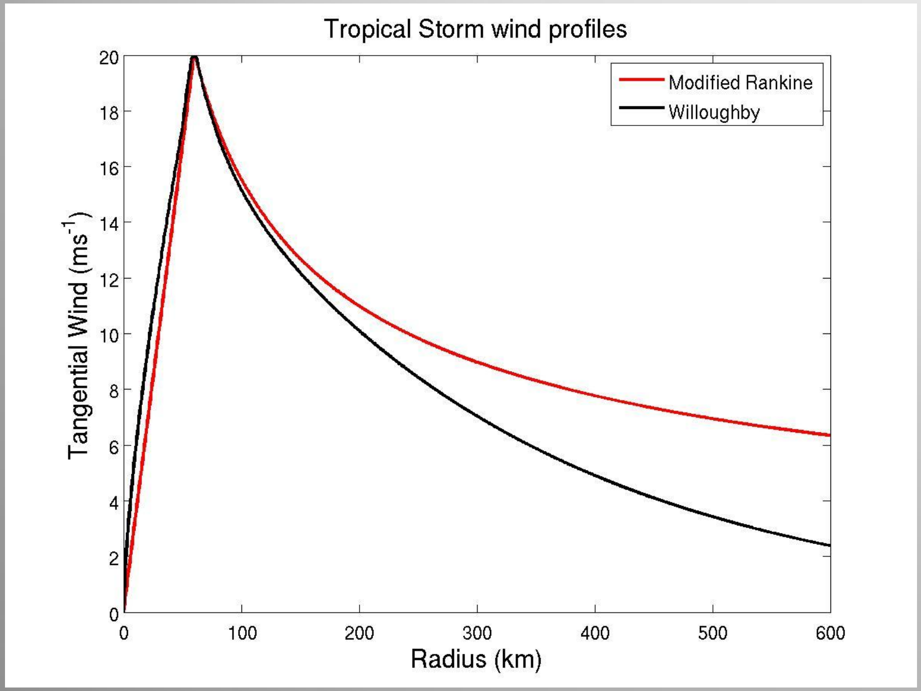
$$V(r) = V_1(1 - w) + V_o w. \qquad R_1 \le r \le R_2$$

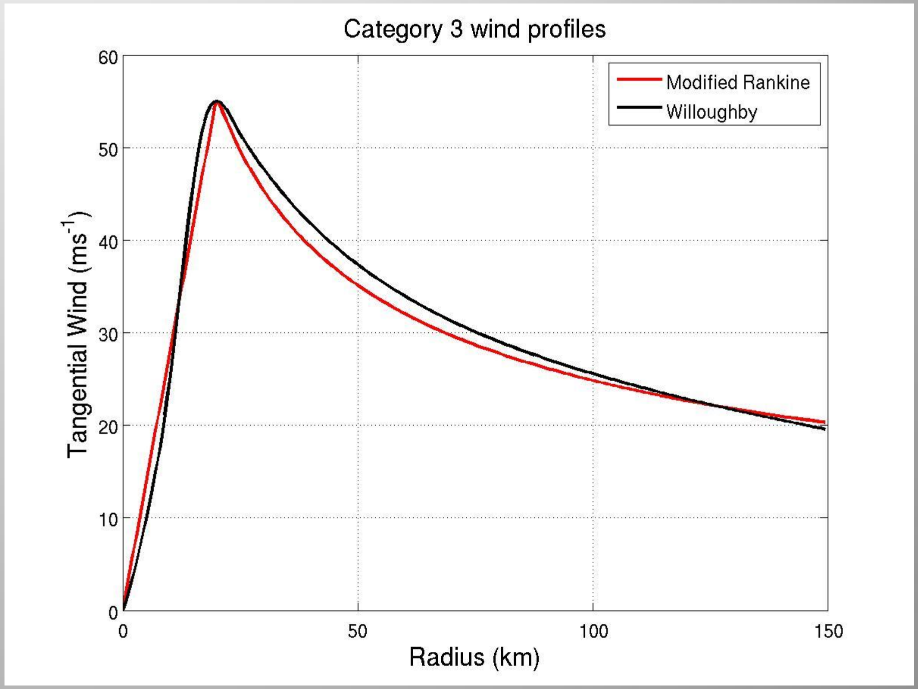
$$V(r) = V_o = V_{max}\left[(1 - A)\exp\left(-\frac{r - R_{max}}{X_1}\right) + A\exp\left(-\frac{r - R_{max}}{X_2}\right)\right] \qquad R_2 \le r$$

**Configurable parameters:** Inner radial structure - $V_{max}$ and $R_{max}$

Outer radial structure – $\alpha$ and $X_2$

# Algorithm – Radial Structure



# Algorithm

- Vortex Removal
- **Vortex Addition**
  - Radial Structure:
    - Modified Rankine Vortex
    - Willoughby Vortex
  - **Vertical Structure:**
    - **Boundary Layer**
    - Free Atmosphere

# Algorithm – Vertical Structure: Boundary Layer

Boundary Layer flow follows Foster (2009):

Steady state, height dependent, axisymmetric flow under a specified wind field.

$$\frac{\partial U}{\partial r} + \frac{U}{r} + \frac{\partial W}{\partial z} = 0.$$

$$U\frac{\partial U}{\partial r} - \frac{V^2}{r} + W\frac{\partial U}{\partial z} - fV = \frac{-1}{\rho_o}\frac{\partial P}{\partial r} + \frac{\partial}{\partial z}(K\frac{\partial U}{\partial z}).$$

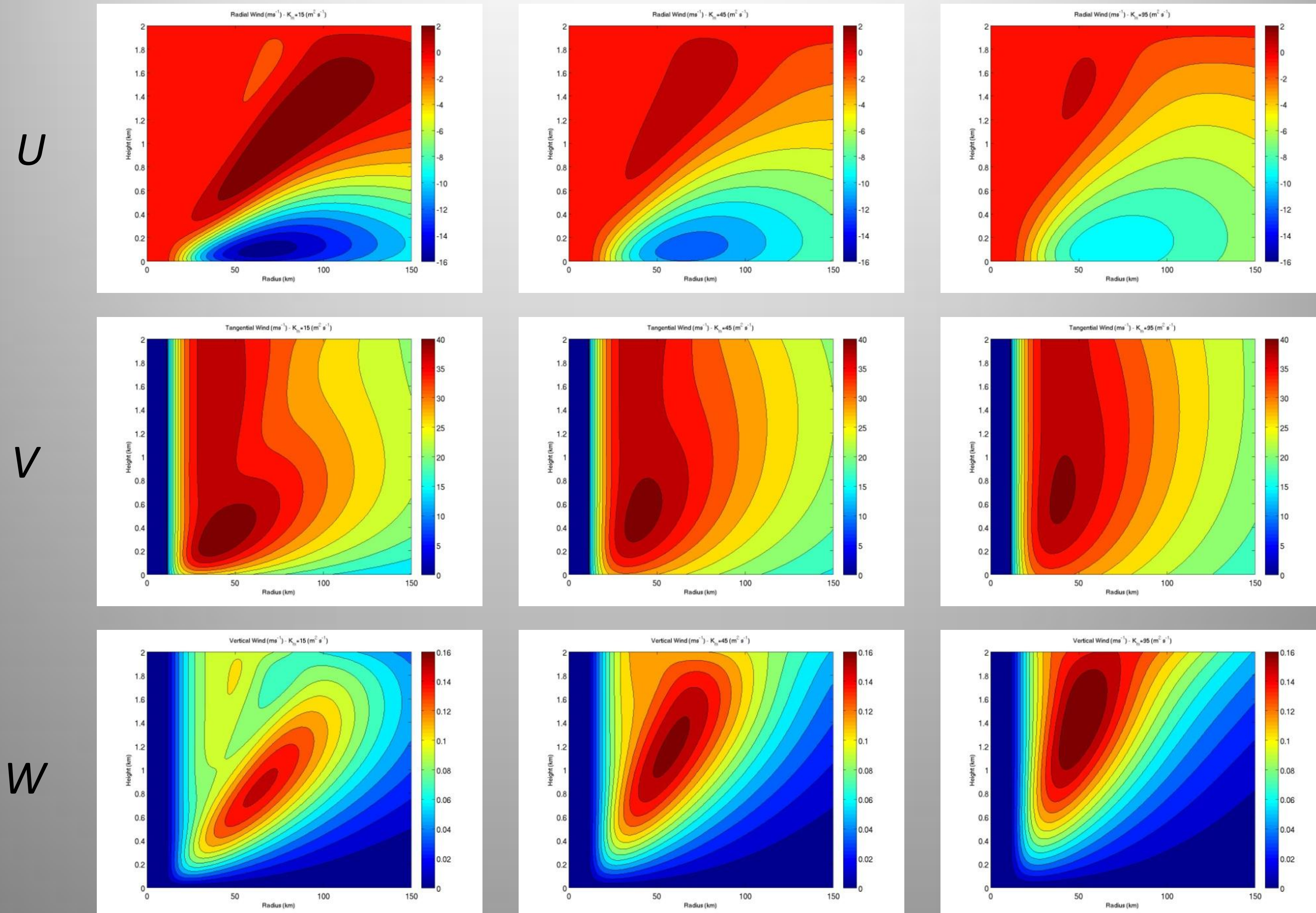
$$U\frac{\partial V}{\partial r} - \frac{UV}{r} + W\frac{\partial V}{\partial z} + fU = \frac{\partial}{\partial z}(K\frac{\partial V}{\partial z}).$$

$$K\frac{\partial (U,V)}{\partial z} = \frac{\tau}{\rho_o} = C_D\left|\vec{V}\right|(U,V).$$

**Configurable parameters:** Boundary layer height and constant eddy diffusivity, *K*

# Algorithm – Vertical Structure: Boundary Layer

Increasing eddy diffusivity, *K* →



# Algorithm

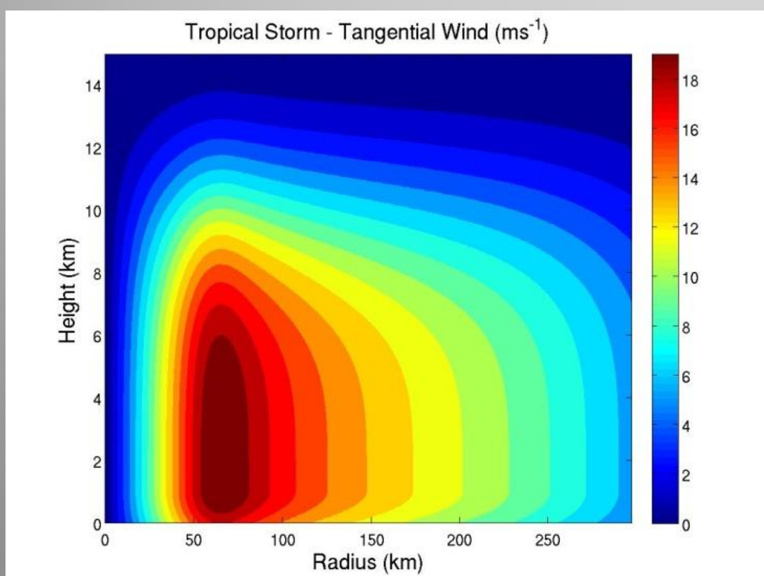
- Vortex Removal
- **Vortex Addition**
  - Radial Structure:
    - Modified Rankine Vortex
    - Willoughby Vortex
  - **Vertical Structure:**
    - Boundary Layer
    - **Free Atmosphere**

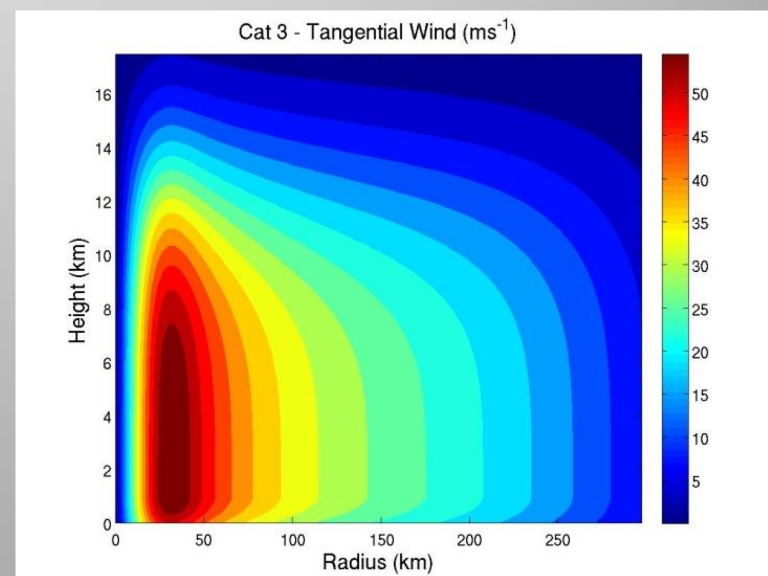
# Algorithm – Vertical Structure: Free Atmosphere

## Gaussian Decay

$$V(r,z) = V(r)\, e^{-\left[\frac{(Z_{max}-z)^{\alpha_1}}{\alpha_1 L_{down}^{\alpha_1}}\right]}. \qquad z < Z_{max}$$

$$V(r,z) = V(r)\, e^{-\left[\frac{(z-Z_{max})^{\alpha_2}}{\alpha_2 L_{up}^{\alpha_2}}\right]}. \qquad Z_{max} \le z$$




**Configurable parameters:** Altitude of maximum tangential wind, $Z_{max}$

Decay parameters, $L_{up}$, $L_{down}$, $\alpha_1$, and $\alpha_2$

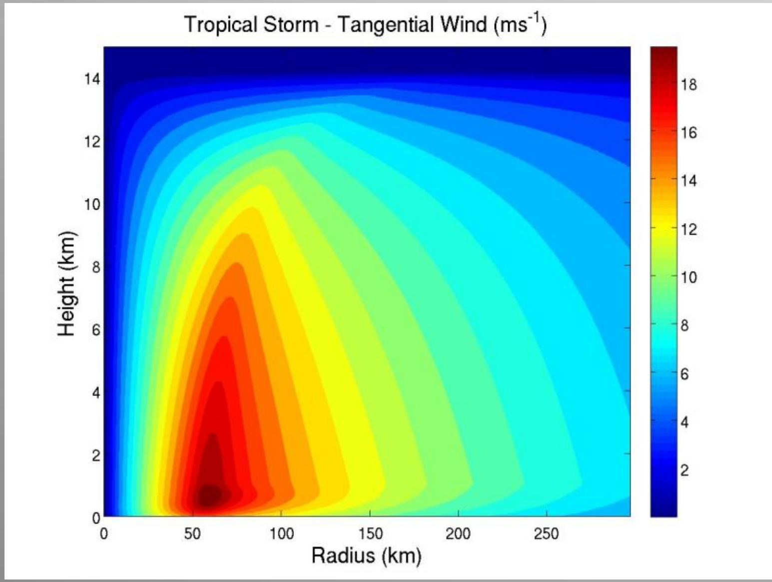
# Algorithm – Vertical Structure: Free Atmosphere

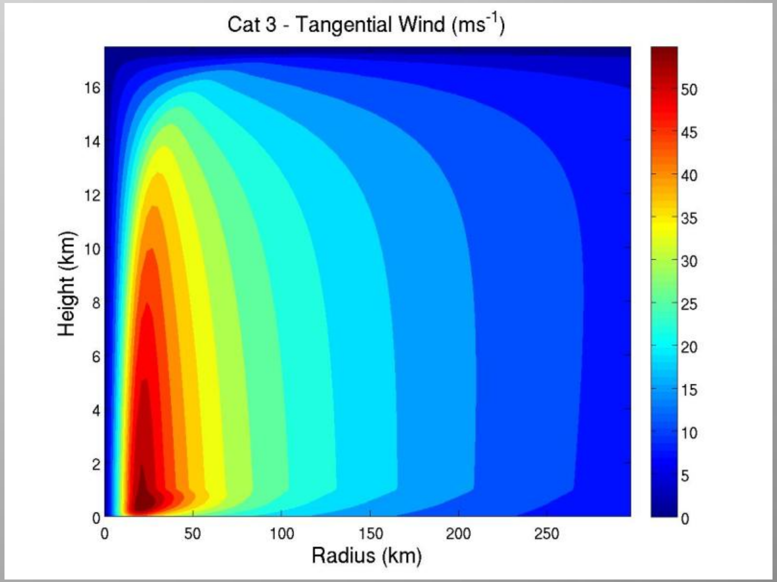
## Emanuel Theory (1986)

•$R_{max}=R_{max}(z)$ using conservation of saturated moist static energy above the boundary layer.

•$V_{max}=V_{max}(z)$ by solving for V at $R_{max}$ noting conservation of angular momentum.

•V(r, z) calculated from V(r) profile at each altitude above the boundary layer.




**Configurable parameters:** Boundary layer height
Outflow temperature (controls height of the vortex)

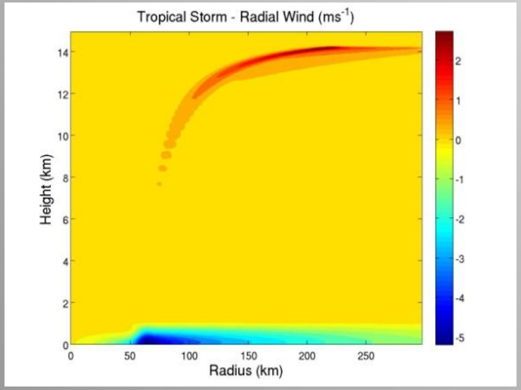
# Algorithm – Vertical Structure: Matching

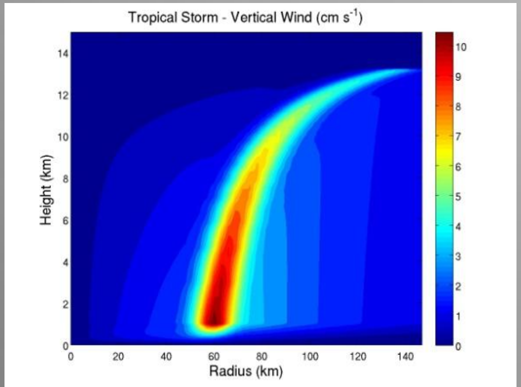
- Absolute angular momentum M(r, z) calculated from V(r,z).

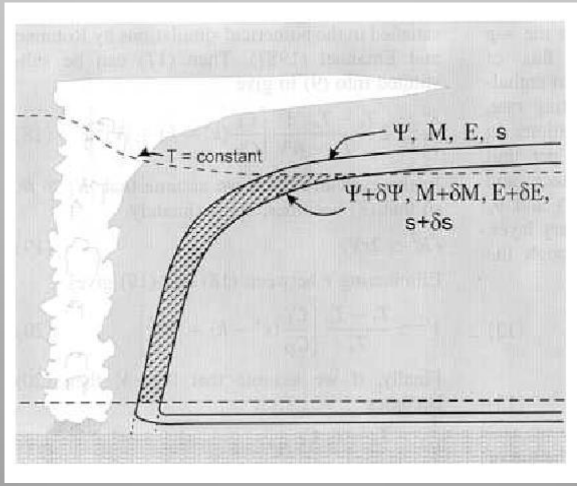
- Ψ(r) is calculated at the boundary layer top through the inward integration of vertical motion. Thus a functional relationship between Ψ an M (or Ψ(M)) is determined.

- Ψ(r, z) = Ψ(M). Maintain constant Ψ along angular momentum surfaces as angular momentum is conserved above the boundary layer.

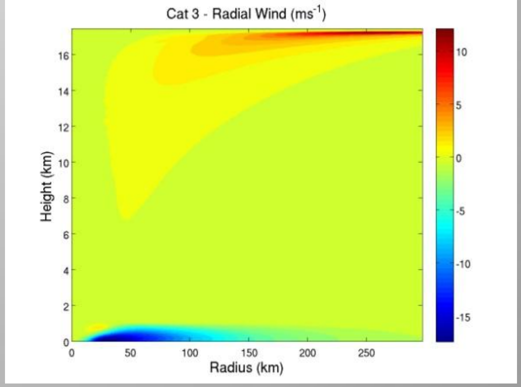
- U(r, z) and W(r, z) determined from Ψ(r, z).

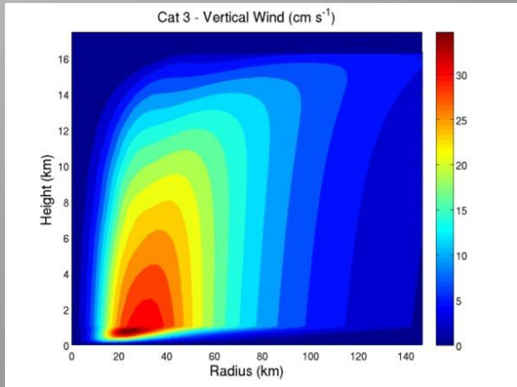



Bister and Emanuel 1998

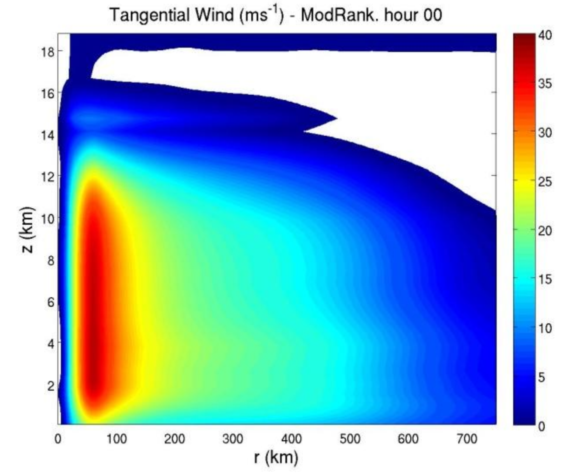


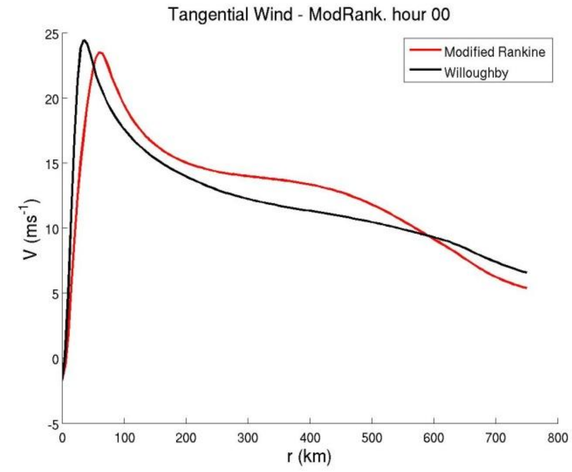



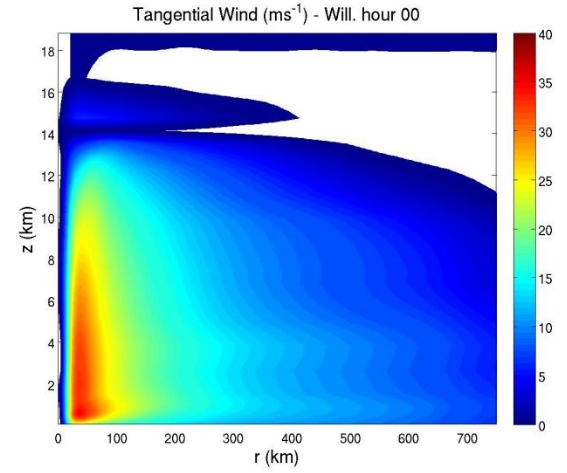
# Testing - Real

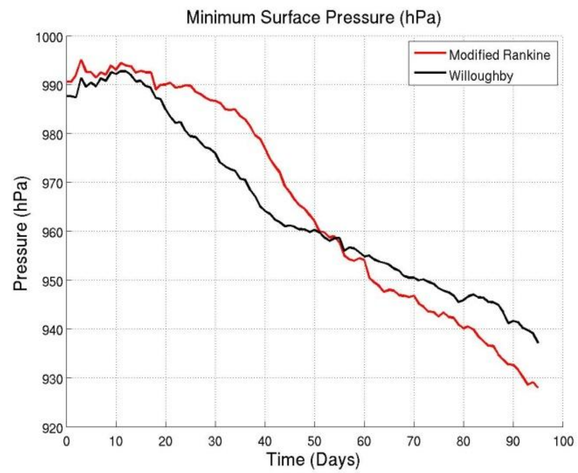
- WRF-ARW 3.1.1.
- 3 Grids (27/9/3 km).
- 40 vertical levels stretched in height.
- YSU boundary layer parameterization.
  - Modified drag formulation (Donelan et al 2004; Davis et al. 2008).
- WRF 6-species microphysics (single-moment).
- RRTM longwave and Goddard shortwave parameterizations
- Grell-Devenyi ensemble cumulus package on outermost grid.

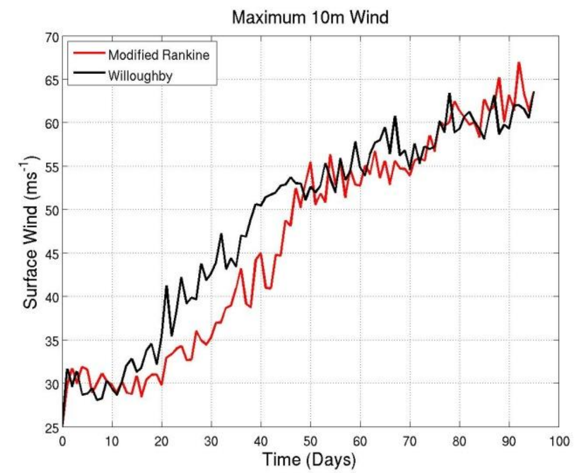
# Modified Rankine (No SC) vs. Willoughby (SC)

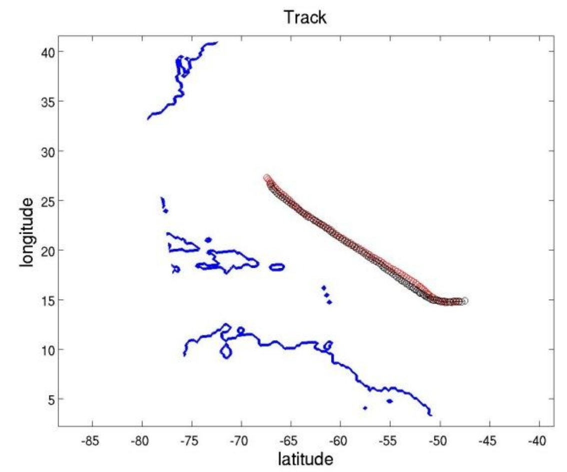


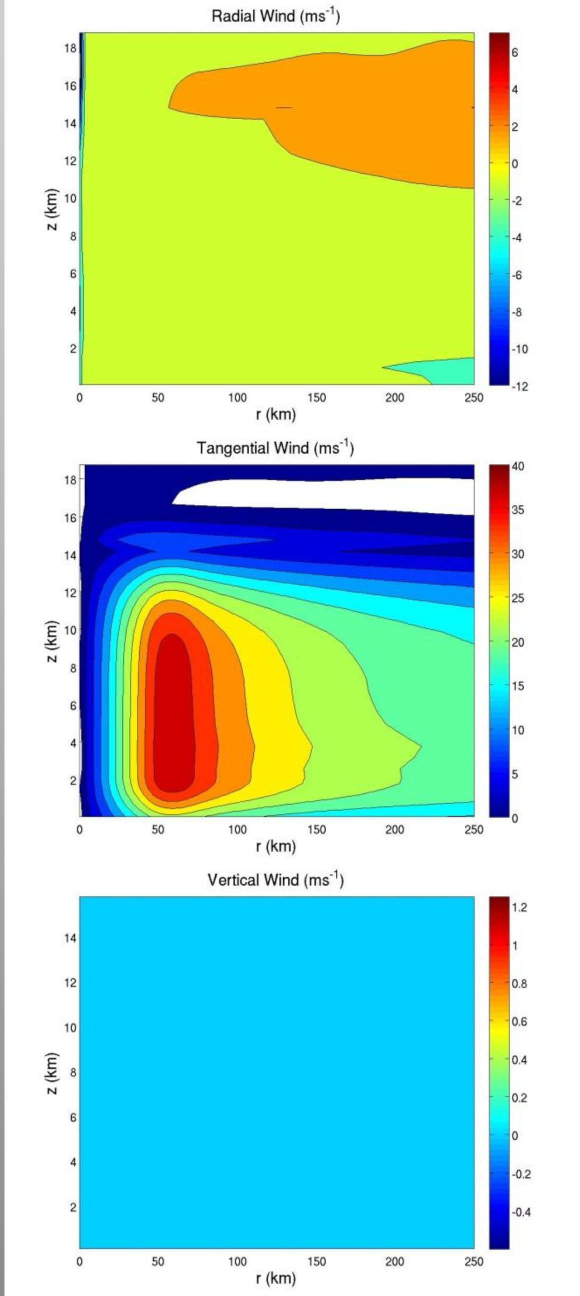



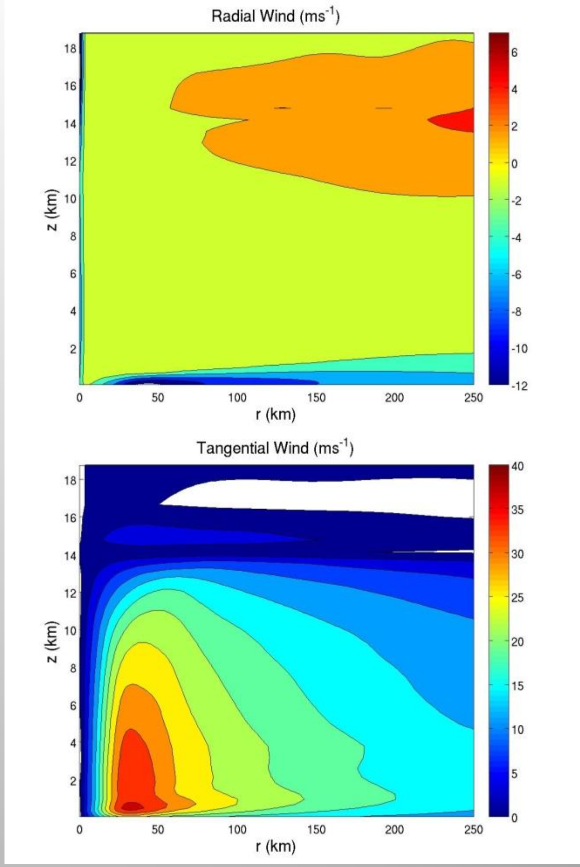
# Real: ModRank (No SC) vs. Willoughby (SC) – Hour 0

*U*

*V*

*W*



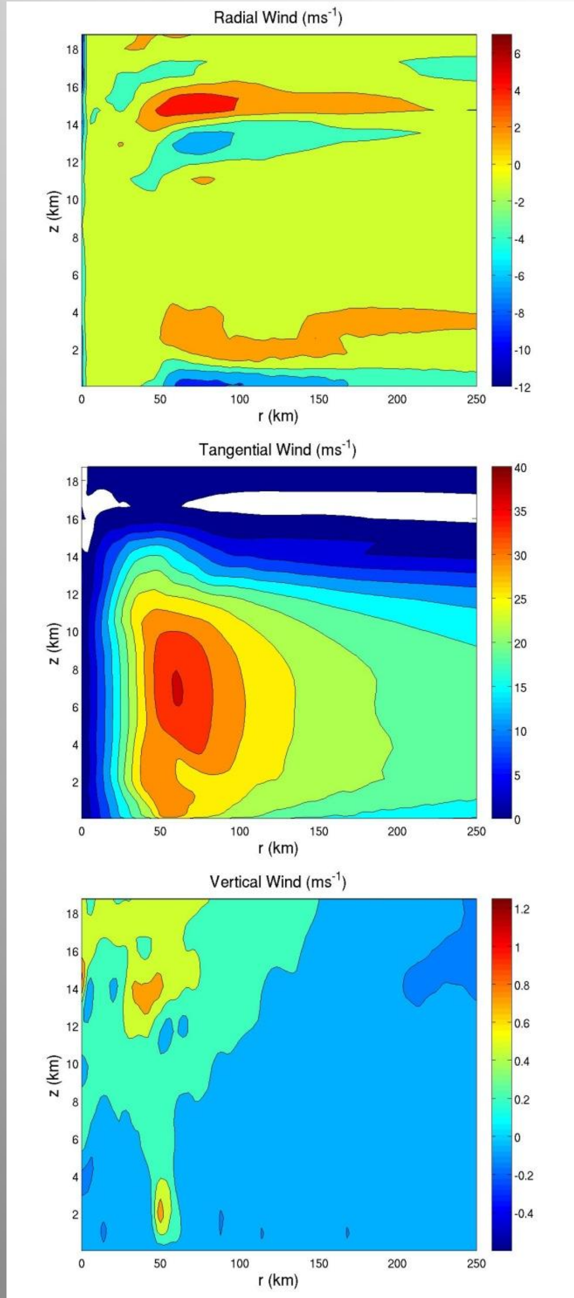



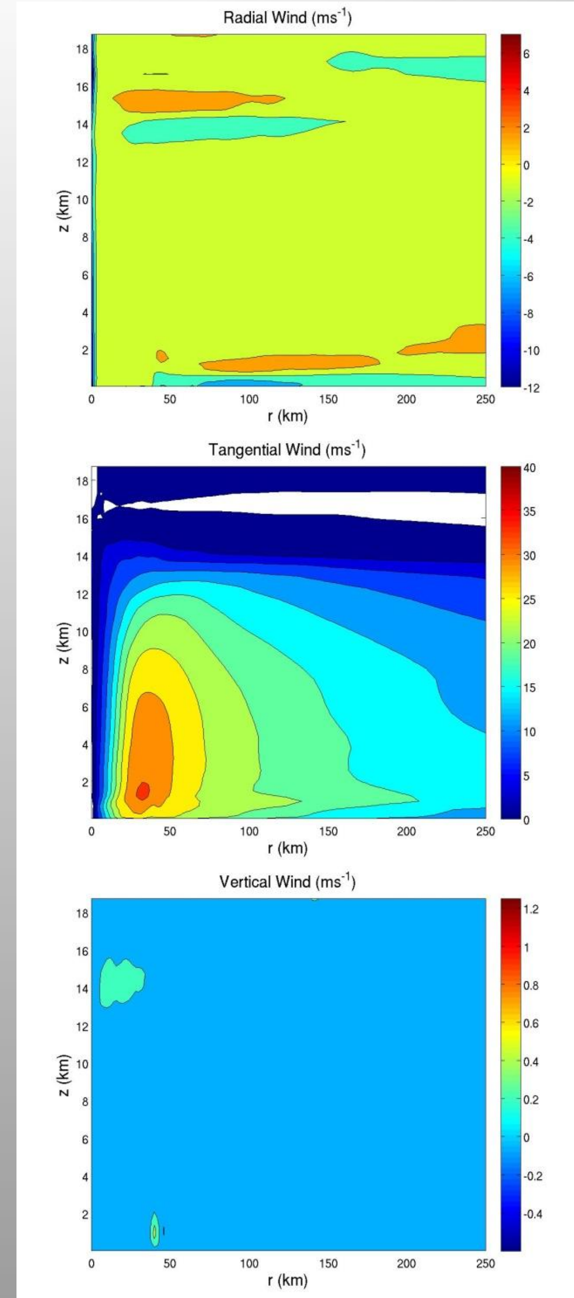
# Real: ModRank (No SC) vs. Willoughby (SC) – Hour 2

*U*

*V*

*W*



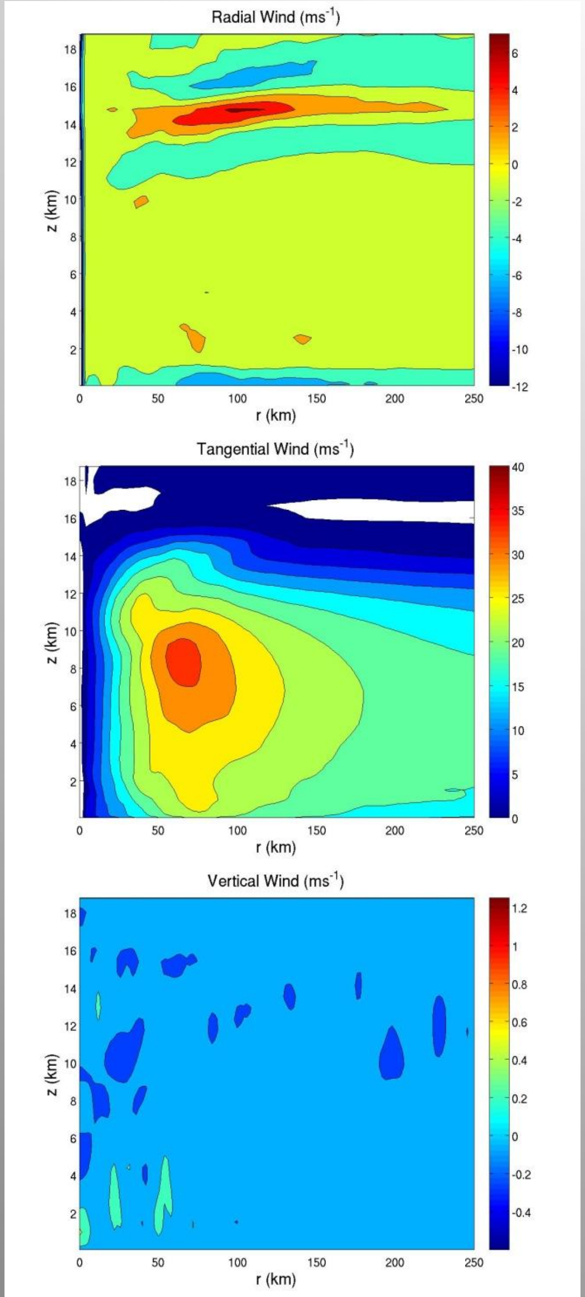



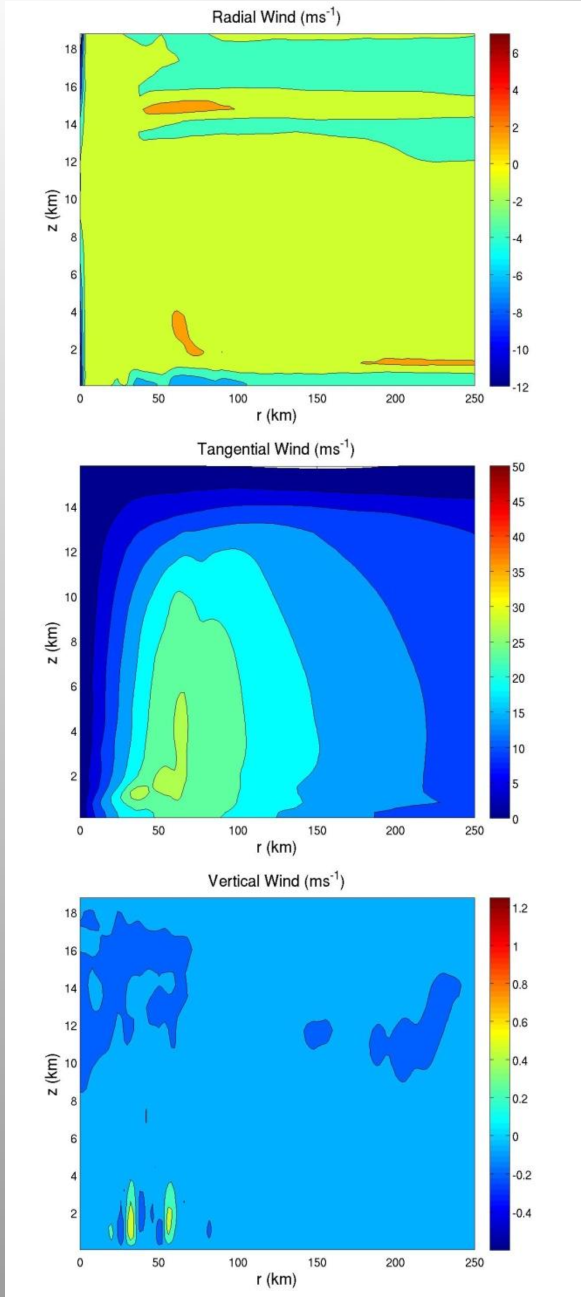
# Real: ModRank (V) vs. Willoughby (UVW) – Hour 4

*U*

*V*

*W*



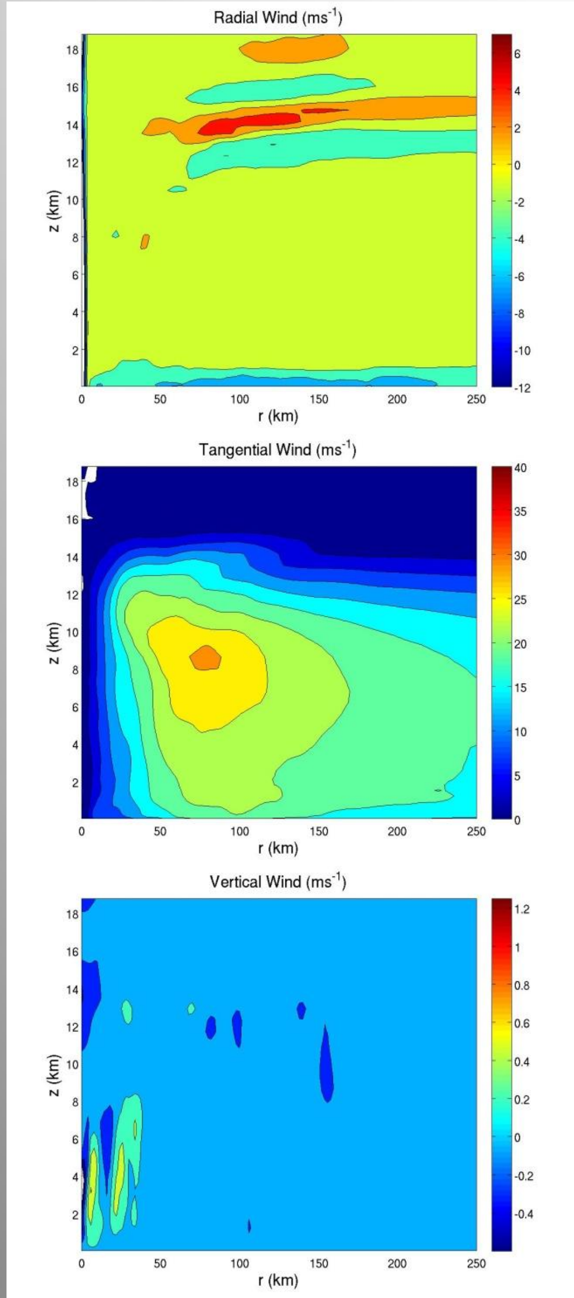



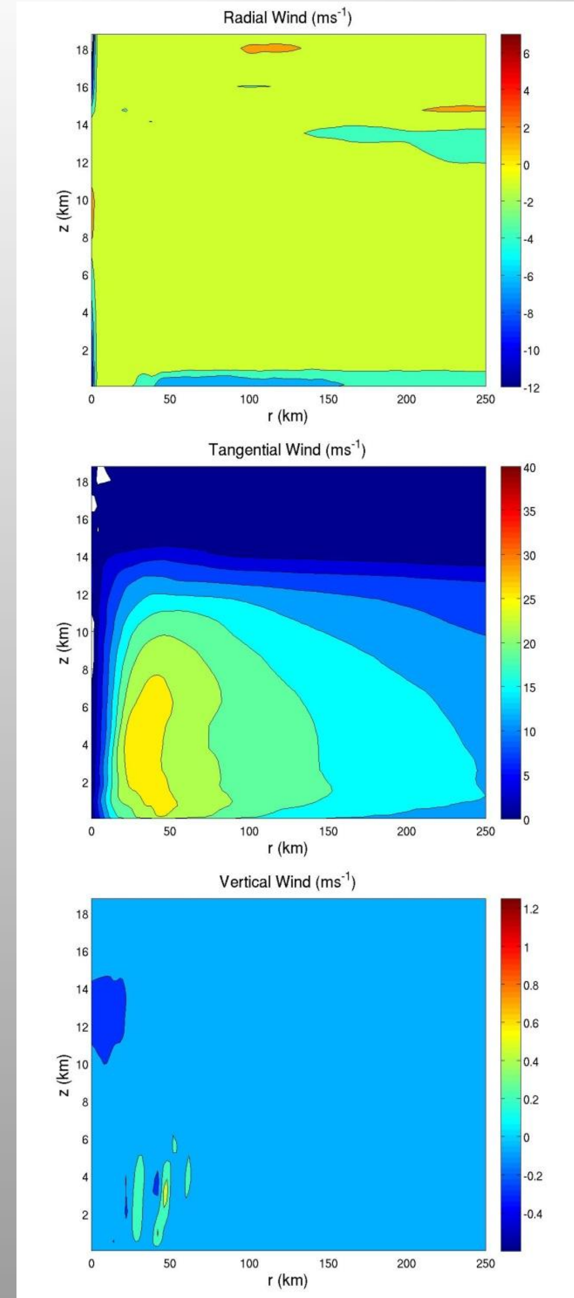
# Real: ModRank (No SC) vs. Willoughby (SC) – Hour 6

*U*

*V*

*W*



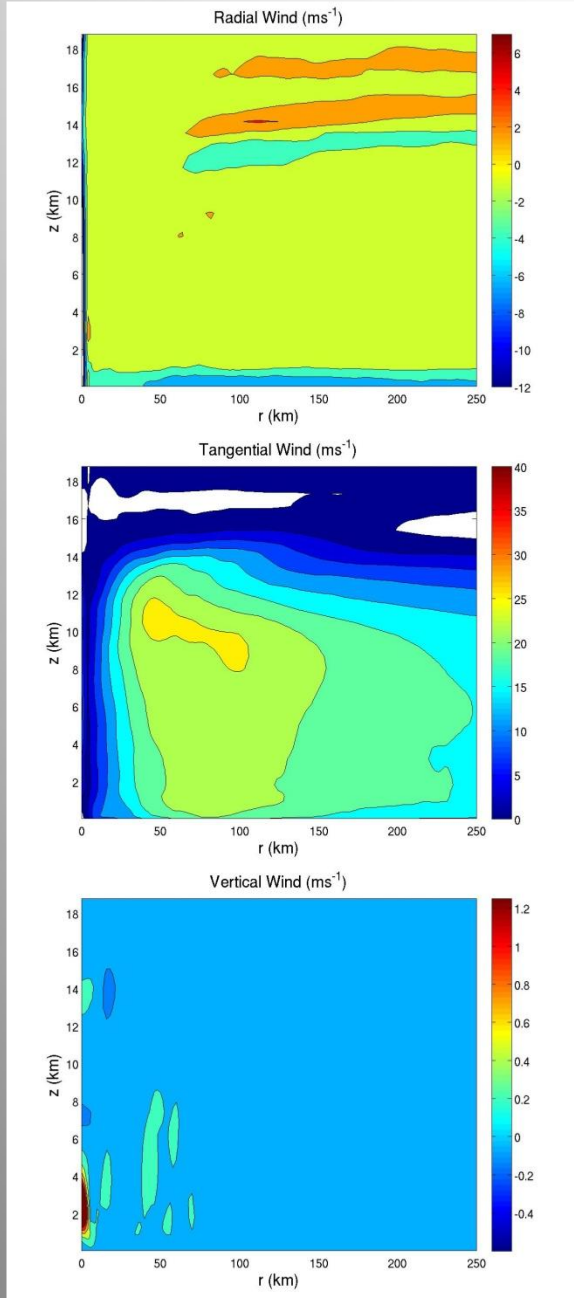



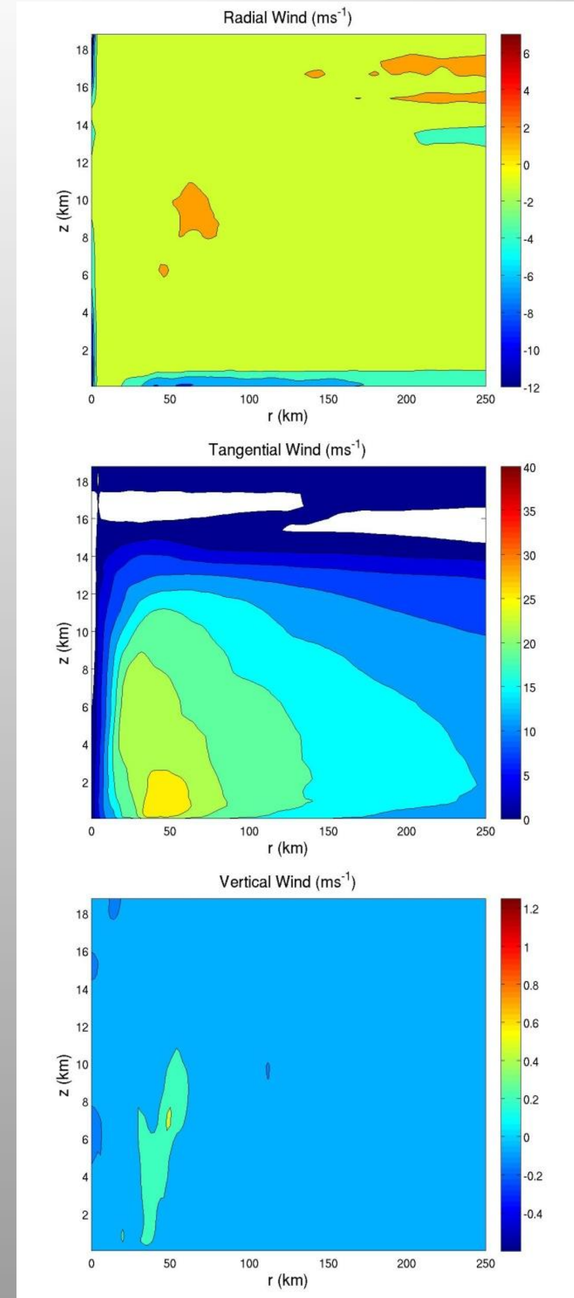
# Real: ModRank (No SC) vs. Willoughby (SC) – Hour 9

*U*

*V*

*W*



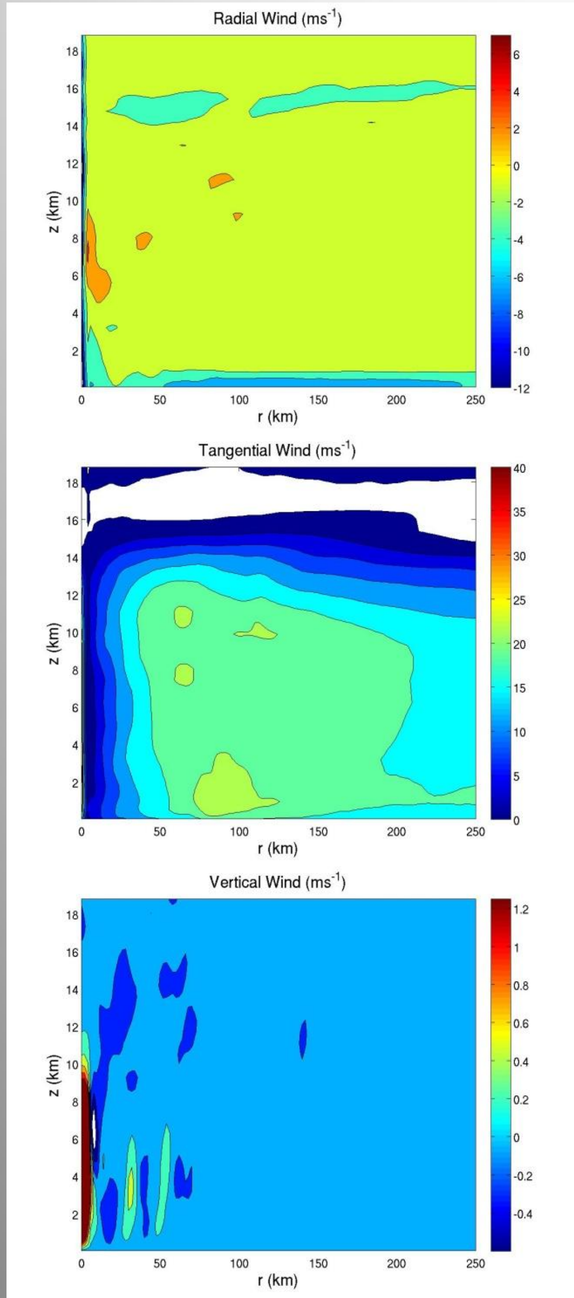



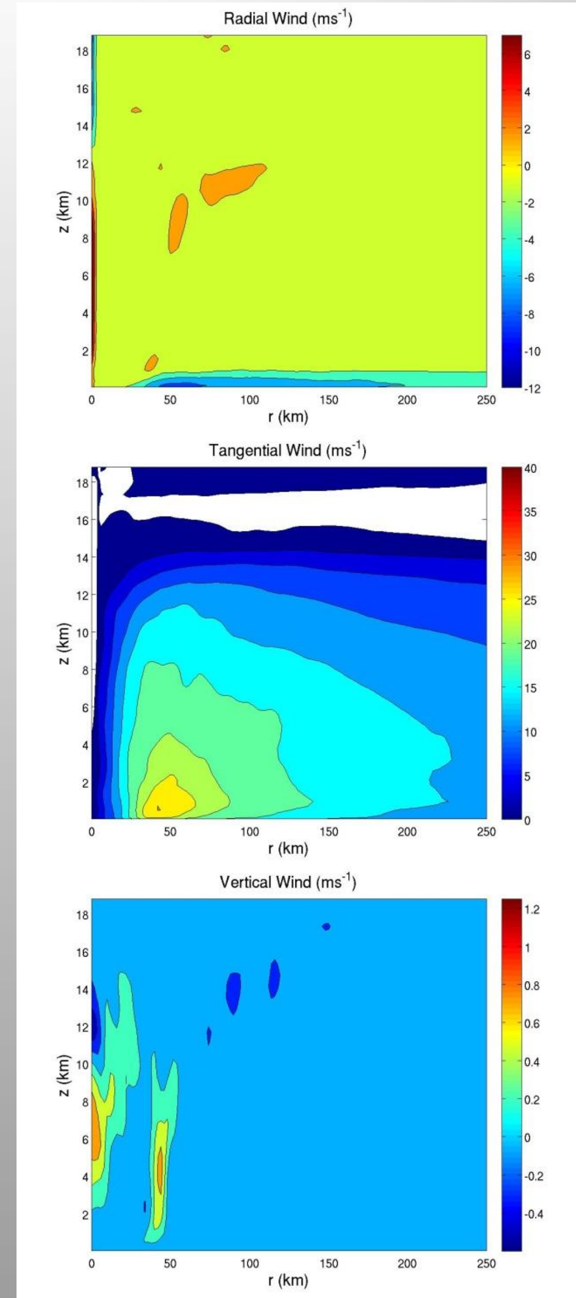
# Real: ModRank (No SC) vs. Willoughby (SC) – Hour 12

*U*

*V*

*W*



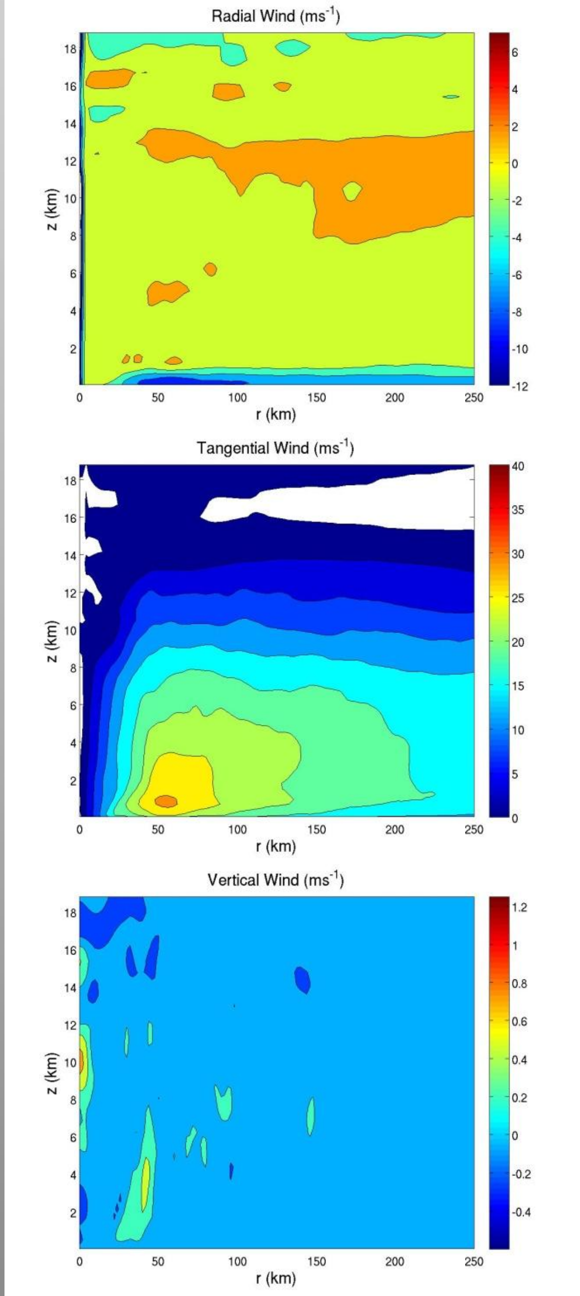



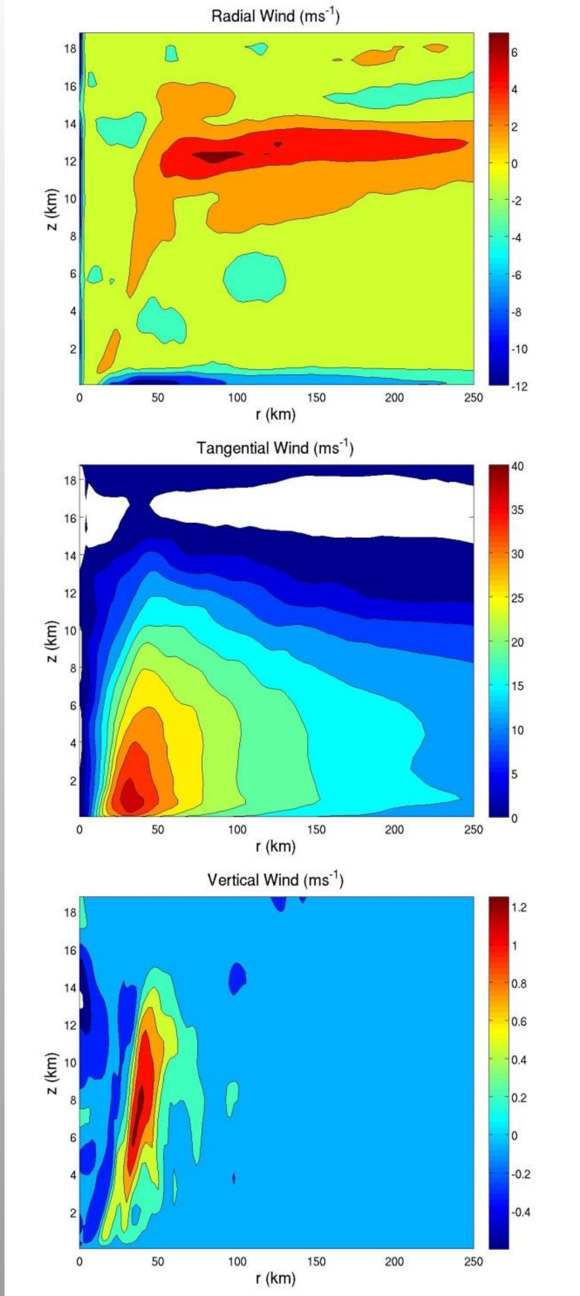
# Real: ModRank (No SC) vs. Willoughby (SC) – Hour 24

*U*

*V*

*W*

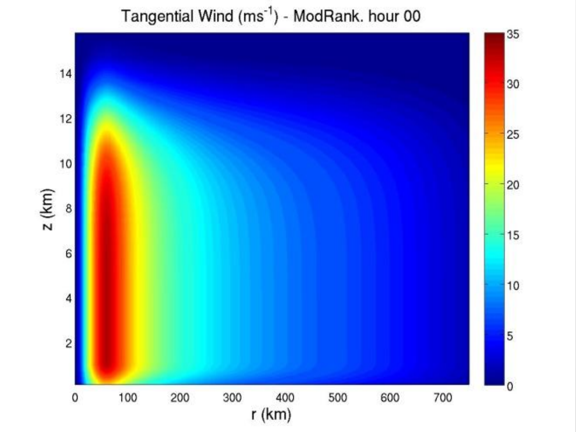


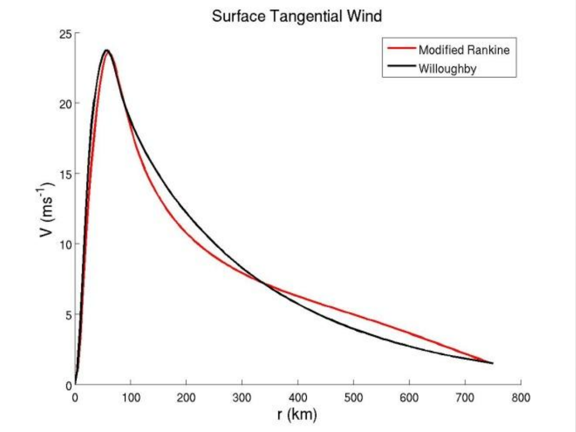



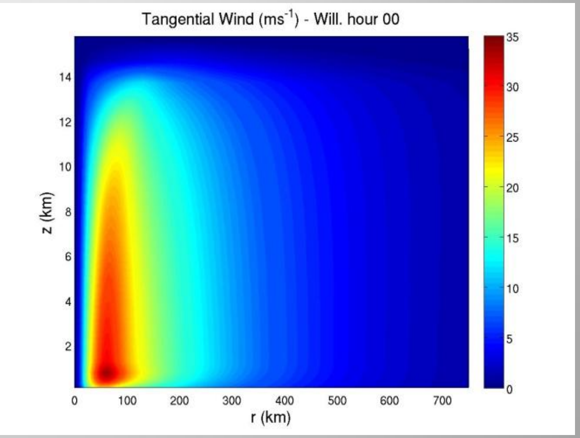
# Testing - Idealized

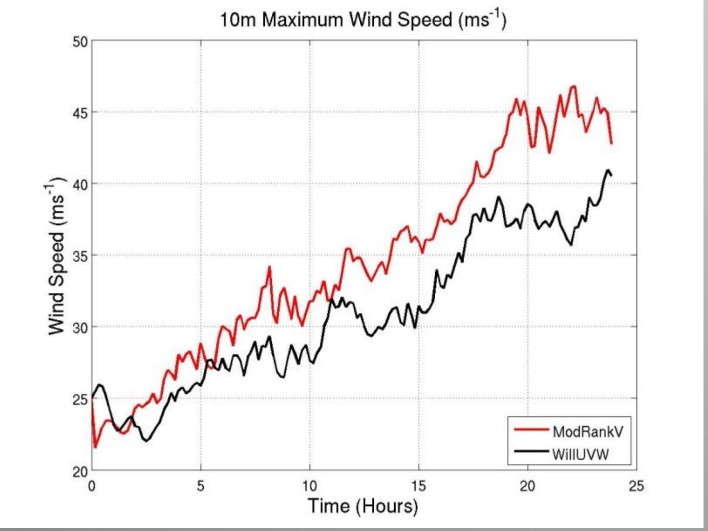
- WRF-ARW 3.1.1.
- Constant SST = 28.5 $^{o}$C.
- No-SAL Jordan sounding.
- No environmental flow.
- 3 Grids (27/9/3 km).
- 40 vertical levels stretched in height.
- No radiation/convection parameterization.
- YSU boundary layer parameterization.
  - Modified drag formulation (Donelan et al 2004; Davis et al. 2008).
- WRF 6-species microphysics (single-moment).

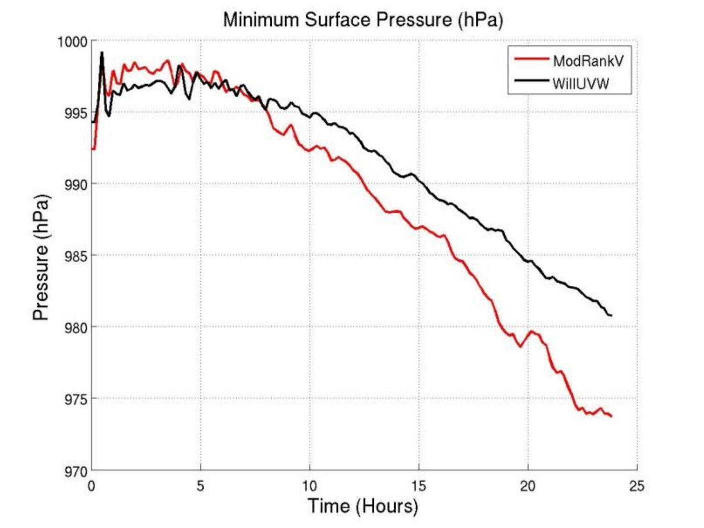
# Ideal: Modified Rankine (No SC) vs. Willoughby (SC)



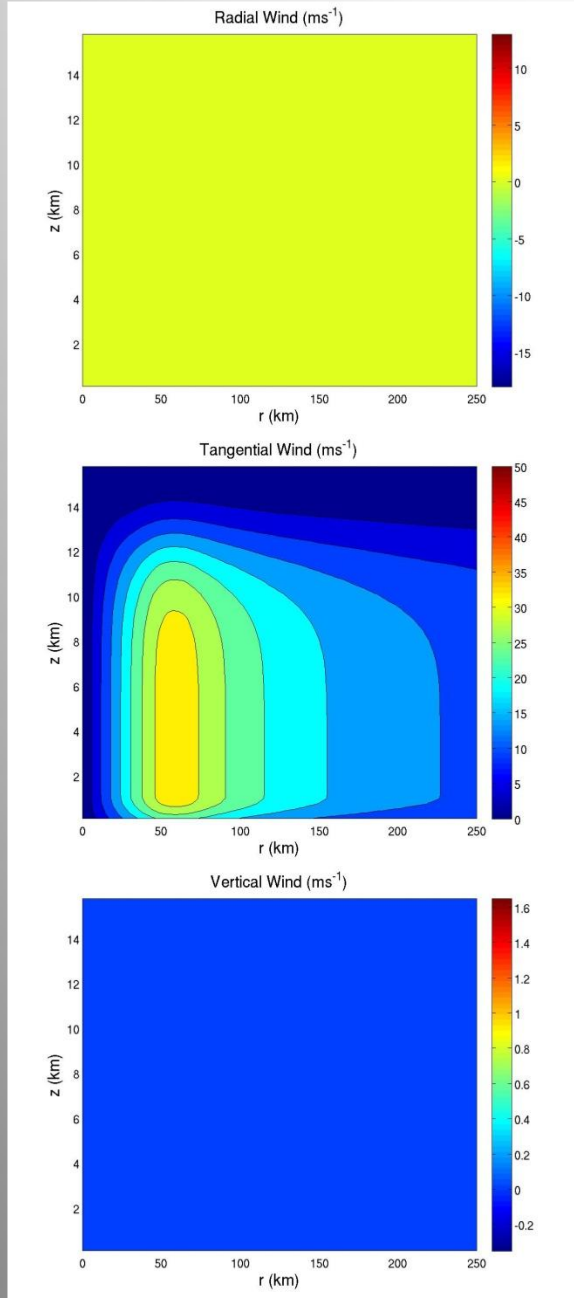



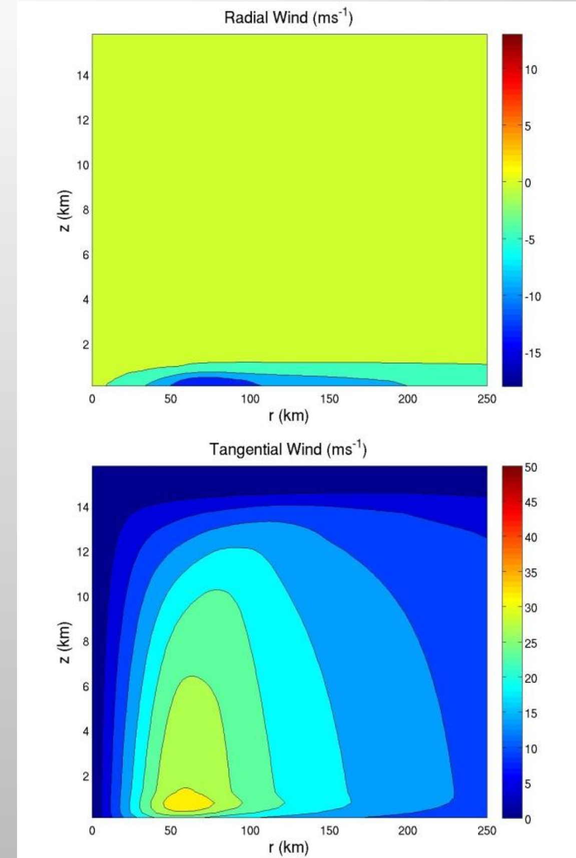
# ModRank (No SC) vs. Willoughby (SC) – Hour 0

*U*

*V*

*W*



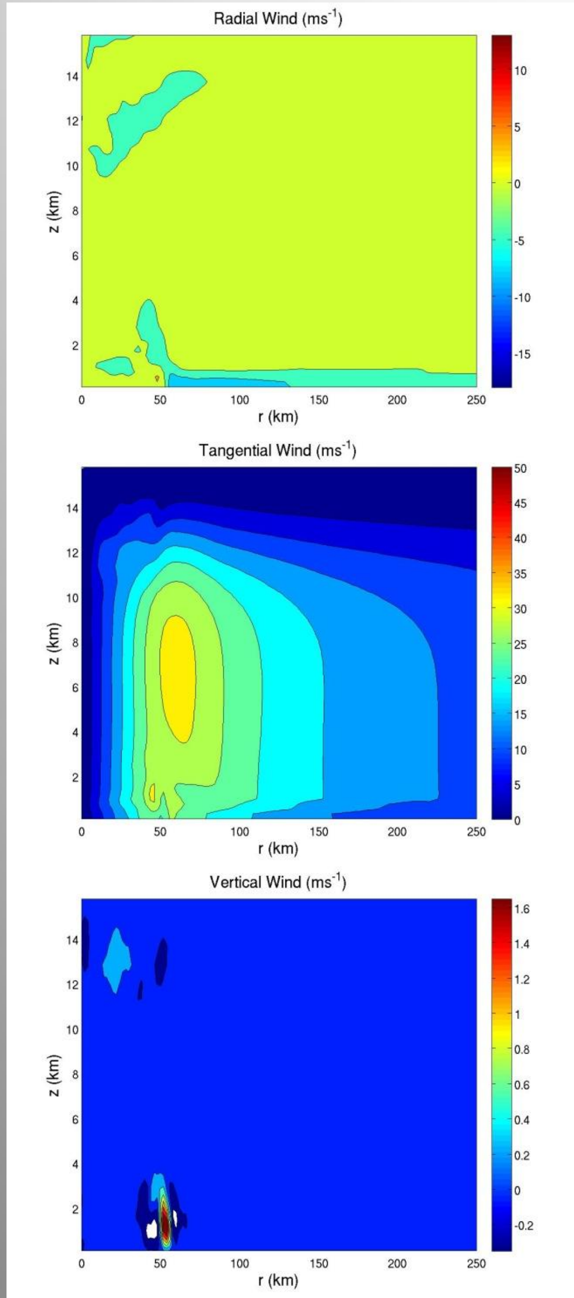



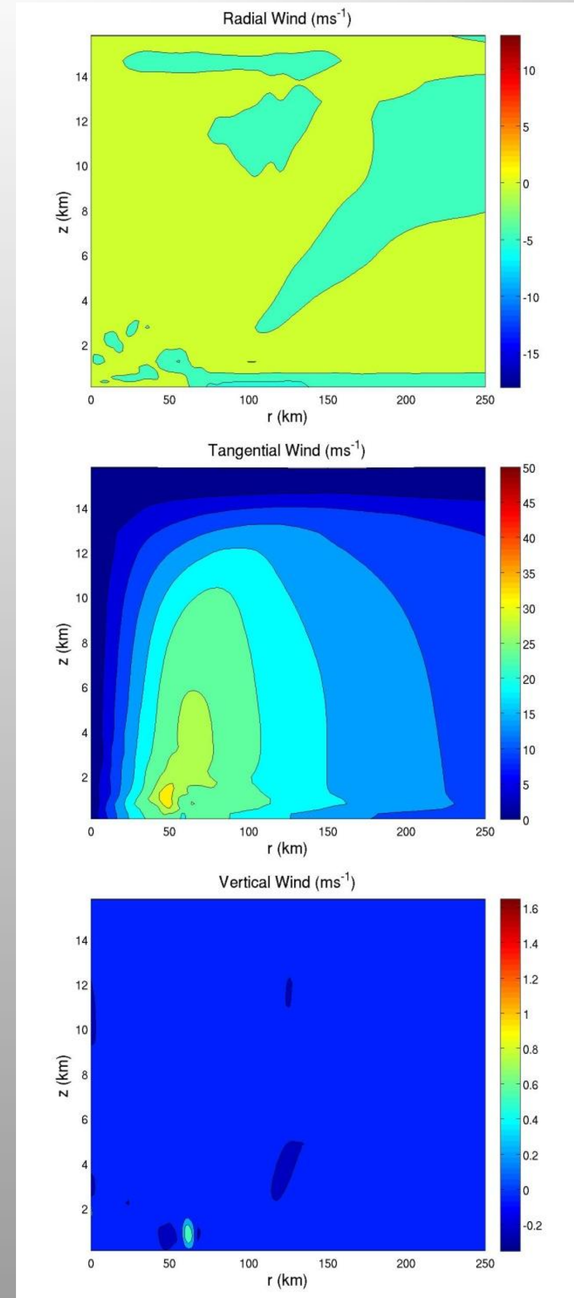
# ModRank (No SC) vs. Willoughby (SC) – Hour 2

*U*

*V*

*W*



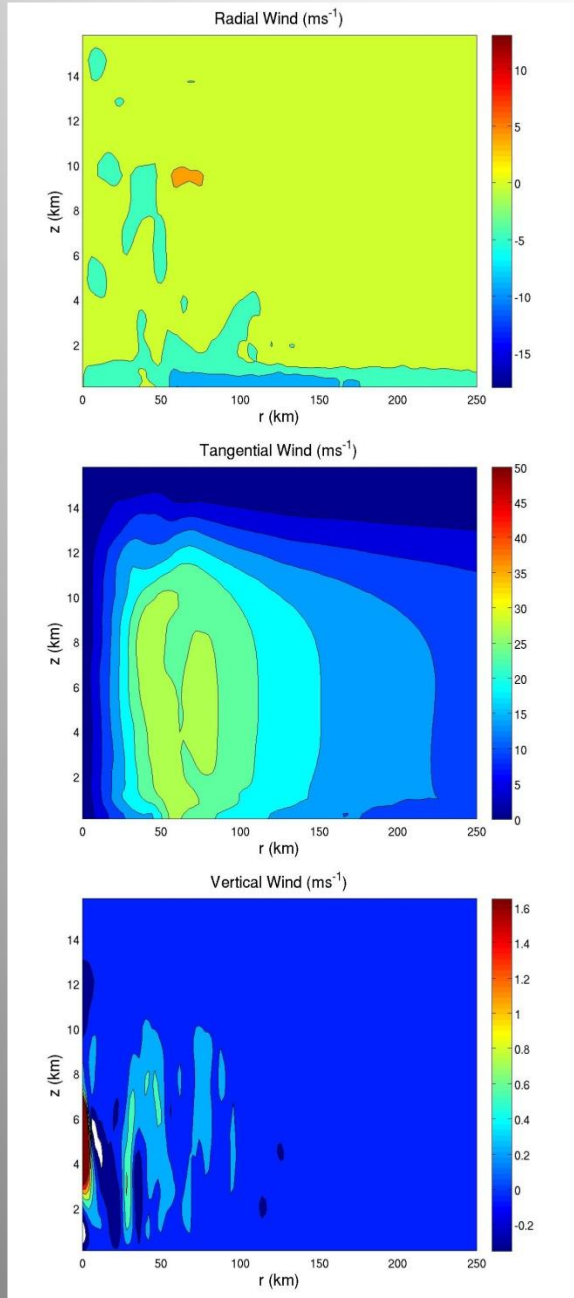



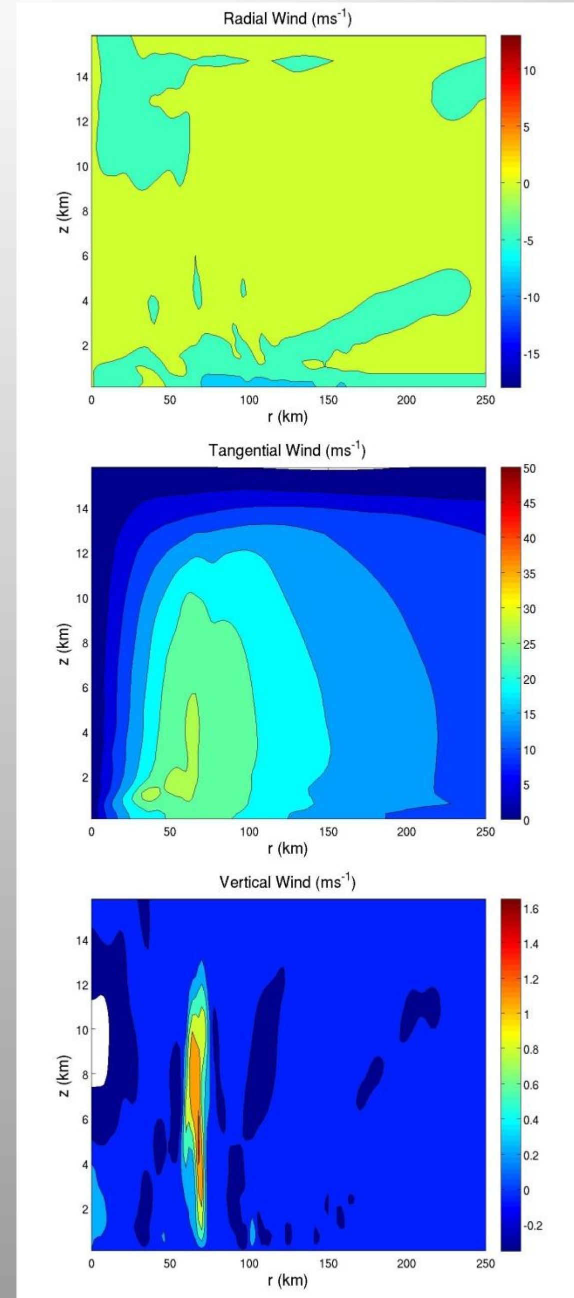
# ModRank (No SC) vs. Willoughby (SC) – Hour 4

*U*

*V*

*W*



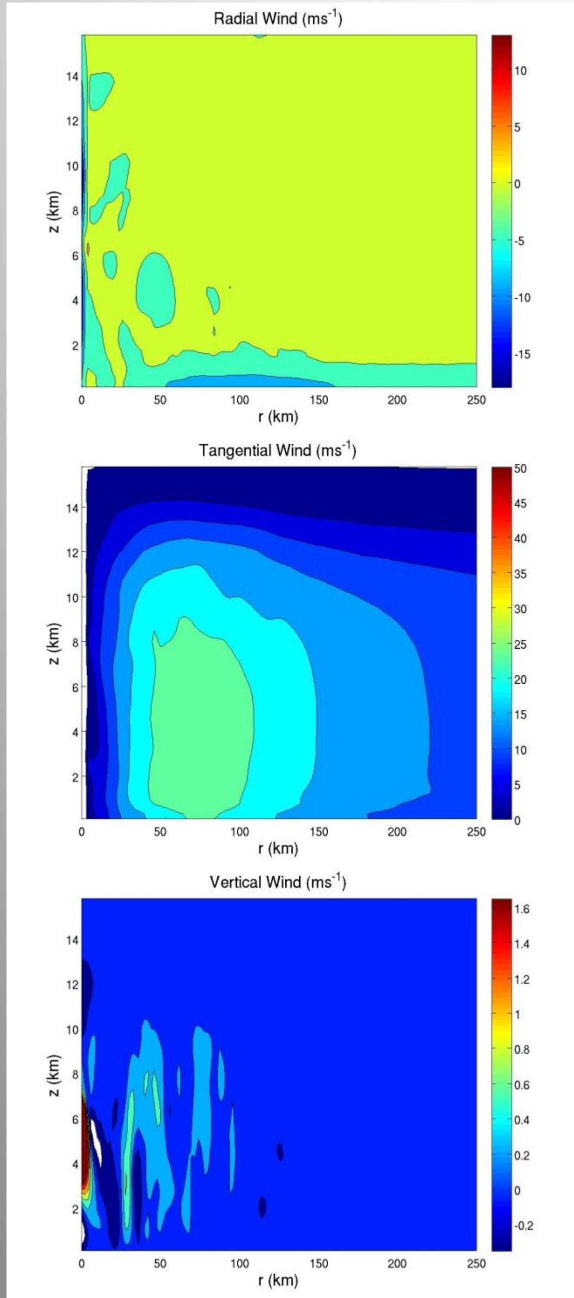



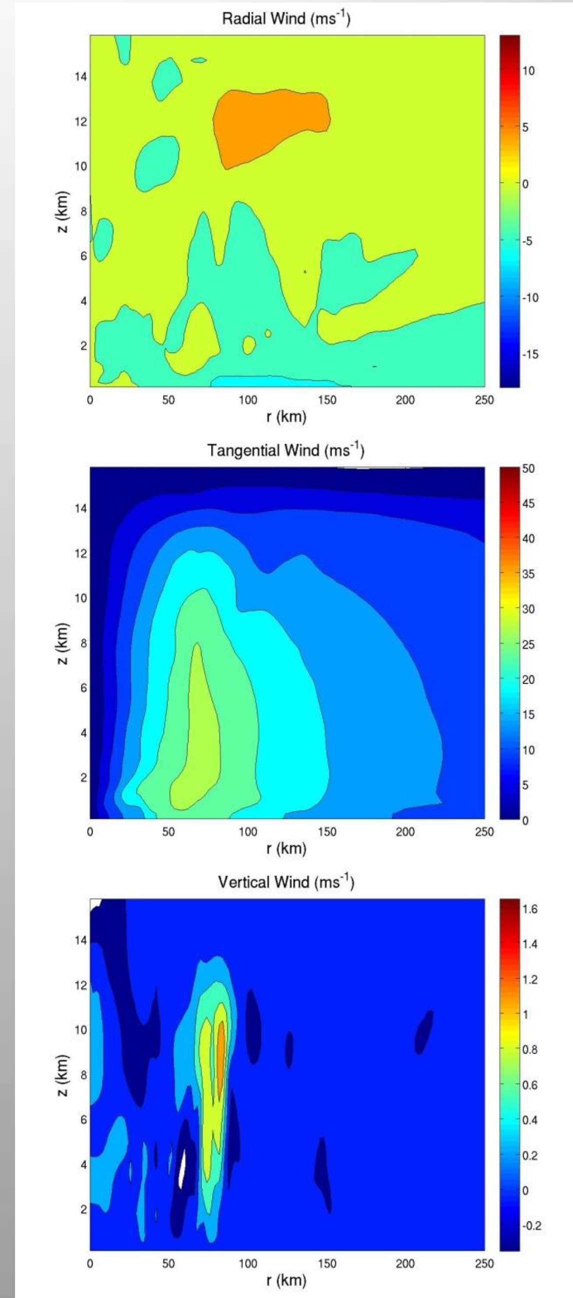
# ModRank (No SC) vs. Willoughby (SC) – Hour 6

*U*

*V*

*W*



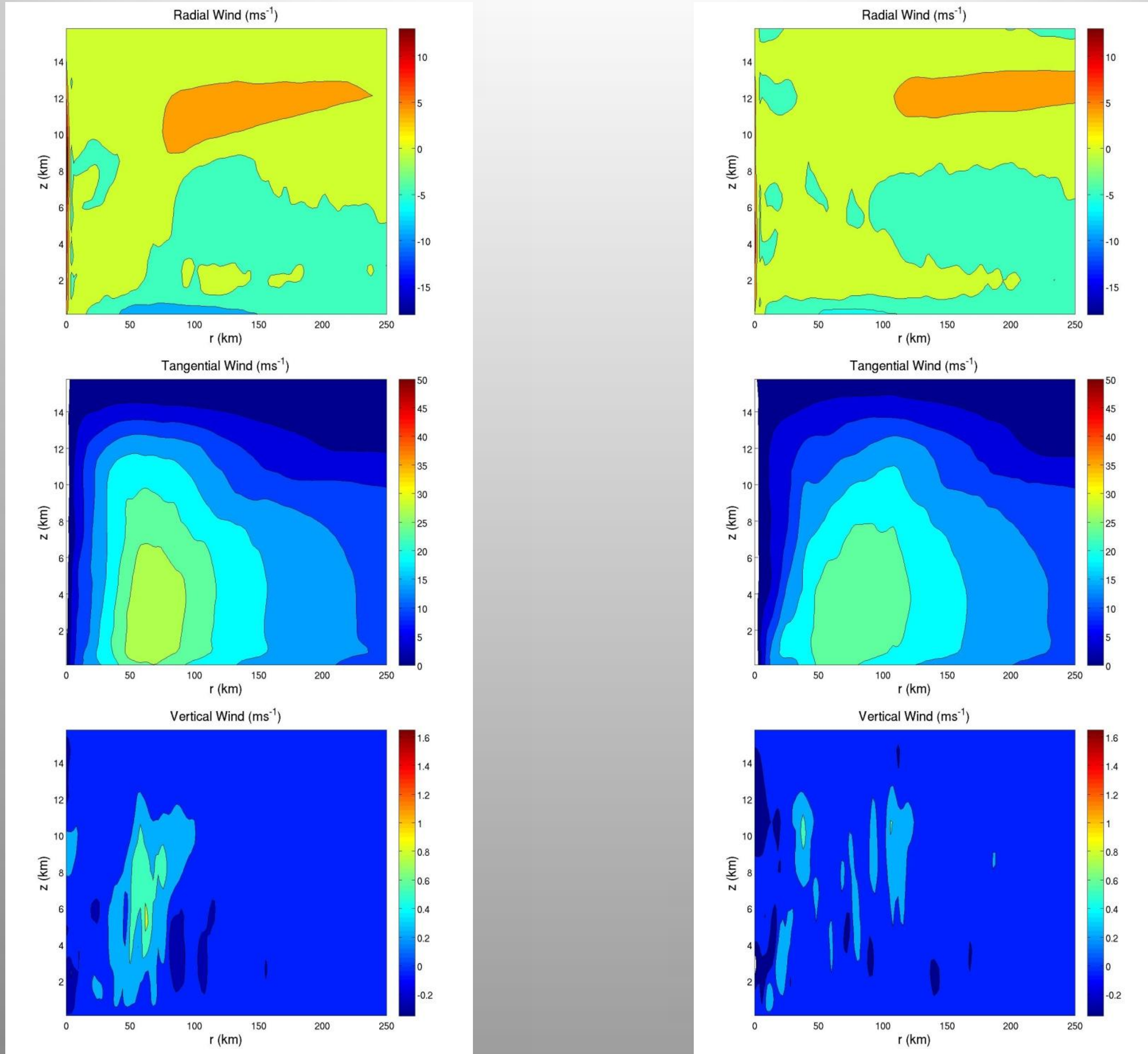



# ModRank (No SC) vs. Willoughby (SC) – Hour 12

*U*

*V*

*W*

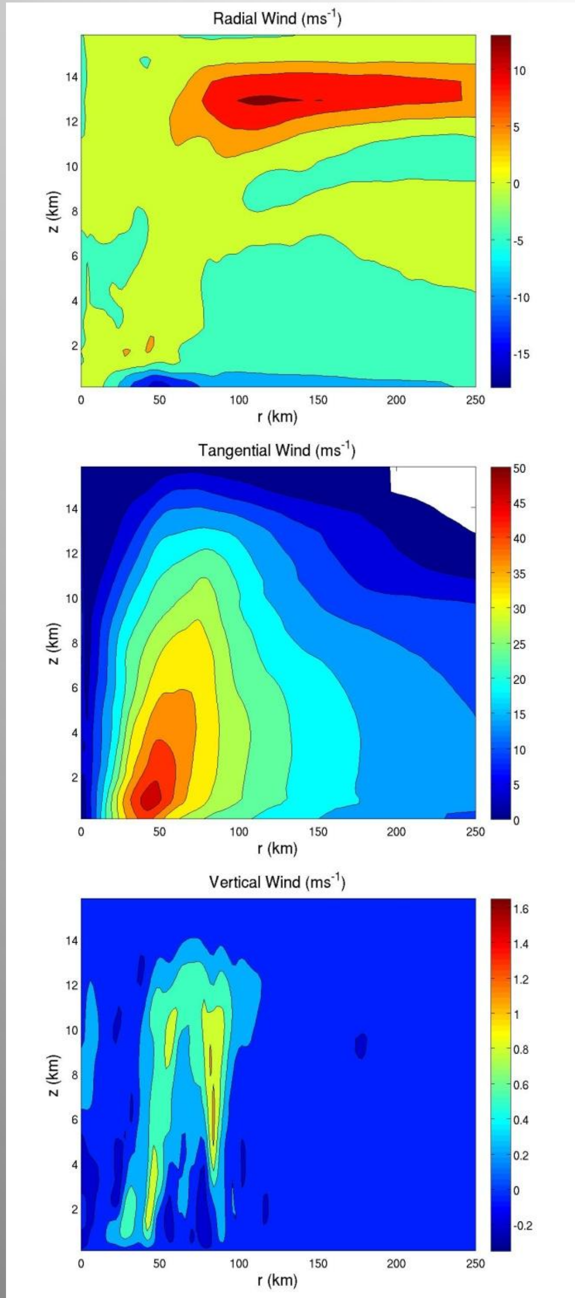


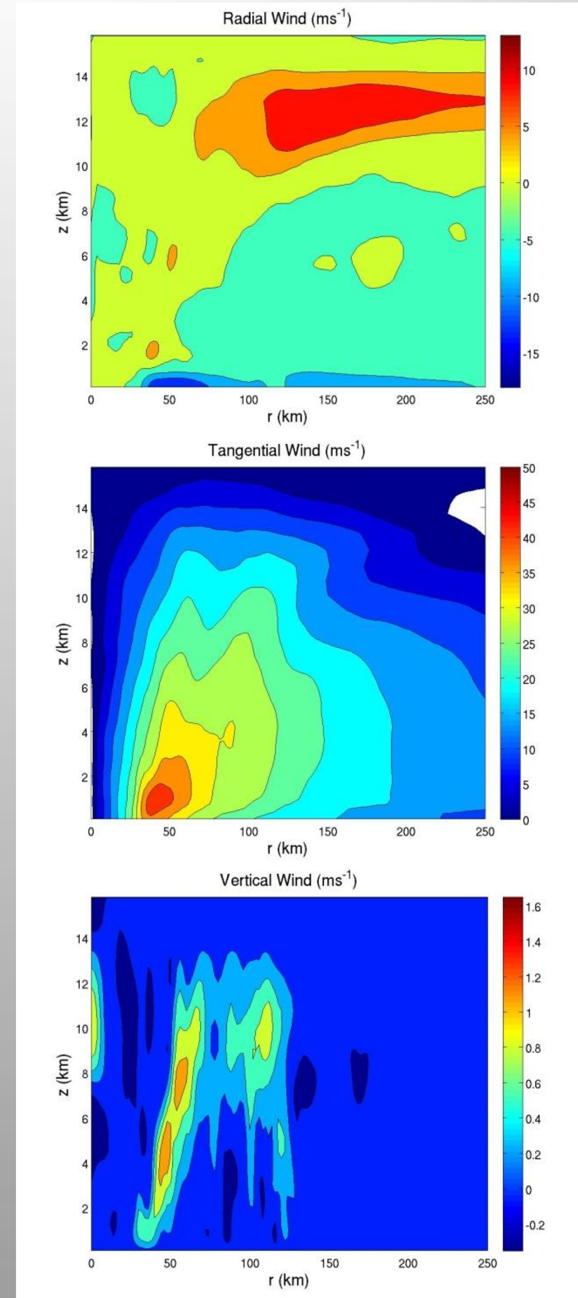
# ModRank (No SC) vs. Willoughby (SC) – Hour 24

*U*

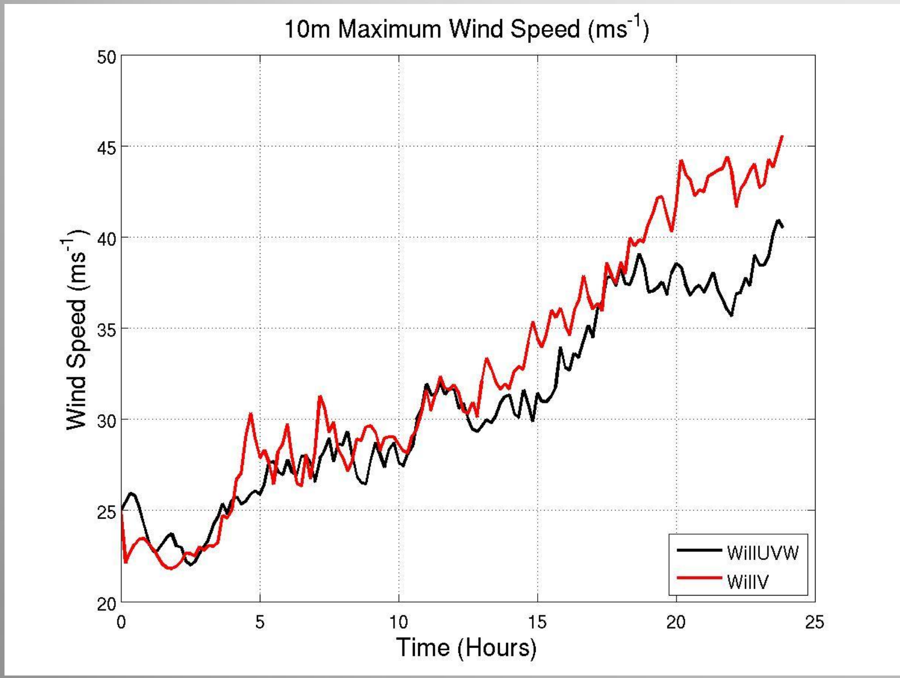
*V*

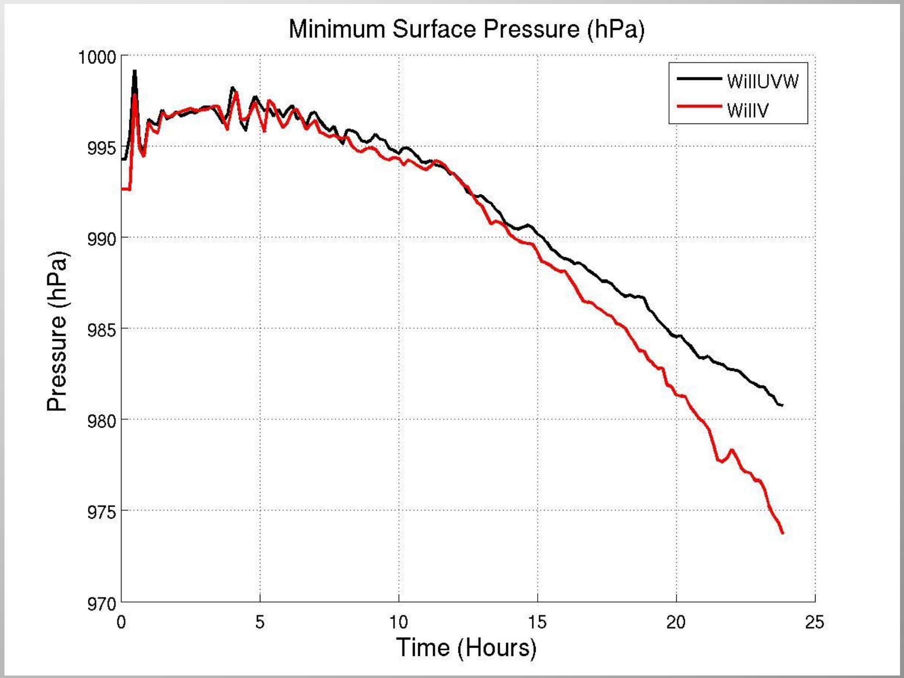
*W*



# Willoughby (SC) vs Willoughby (No SC)



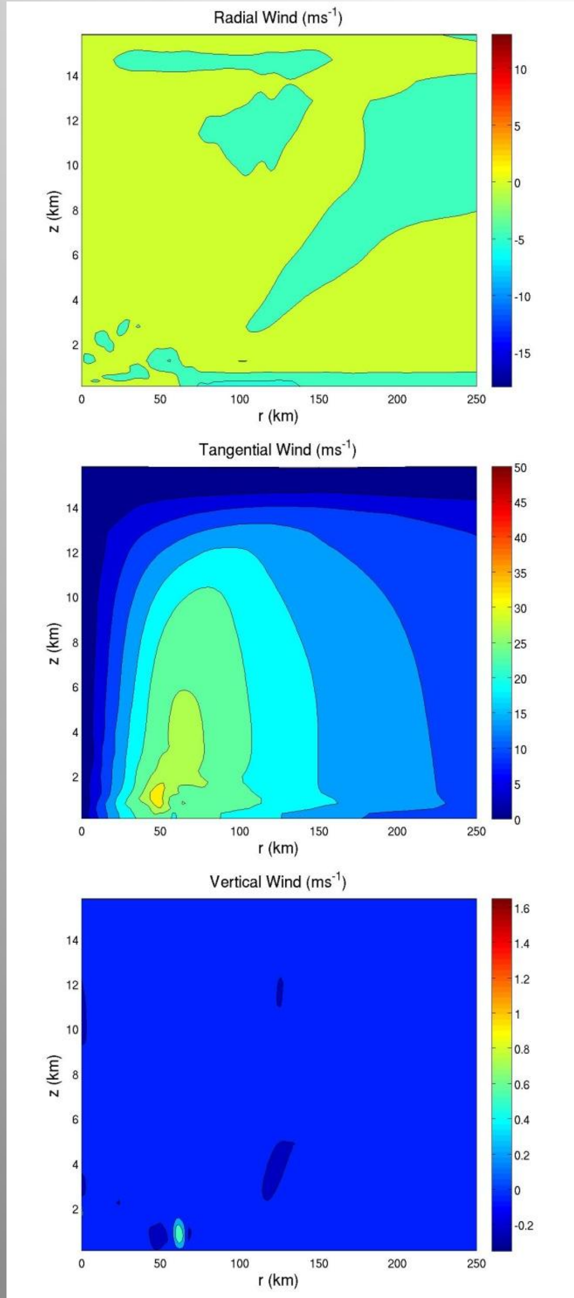



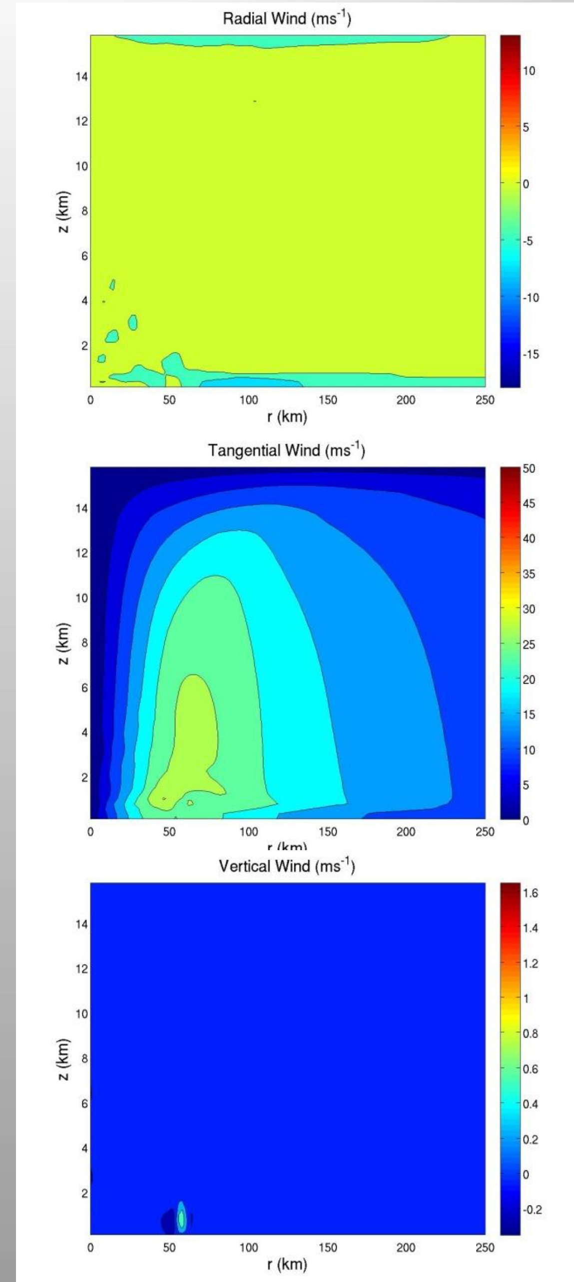
# Willoughby (SC) vs. Willoughby (No SC) – Hour 2

*U*

*V*

*W*



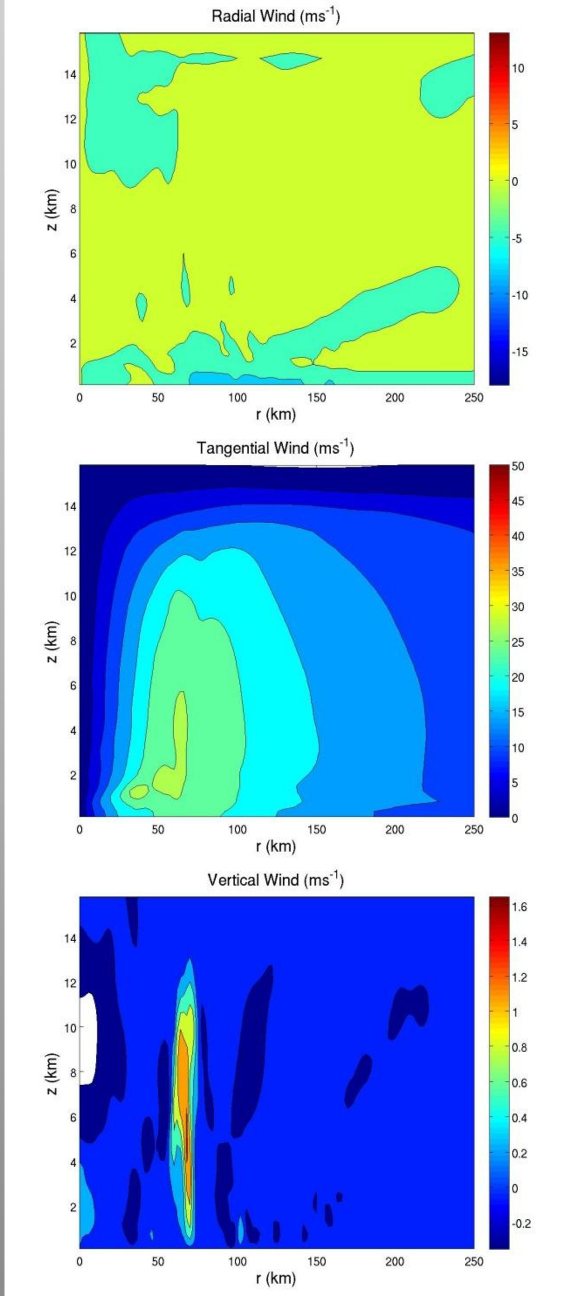



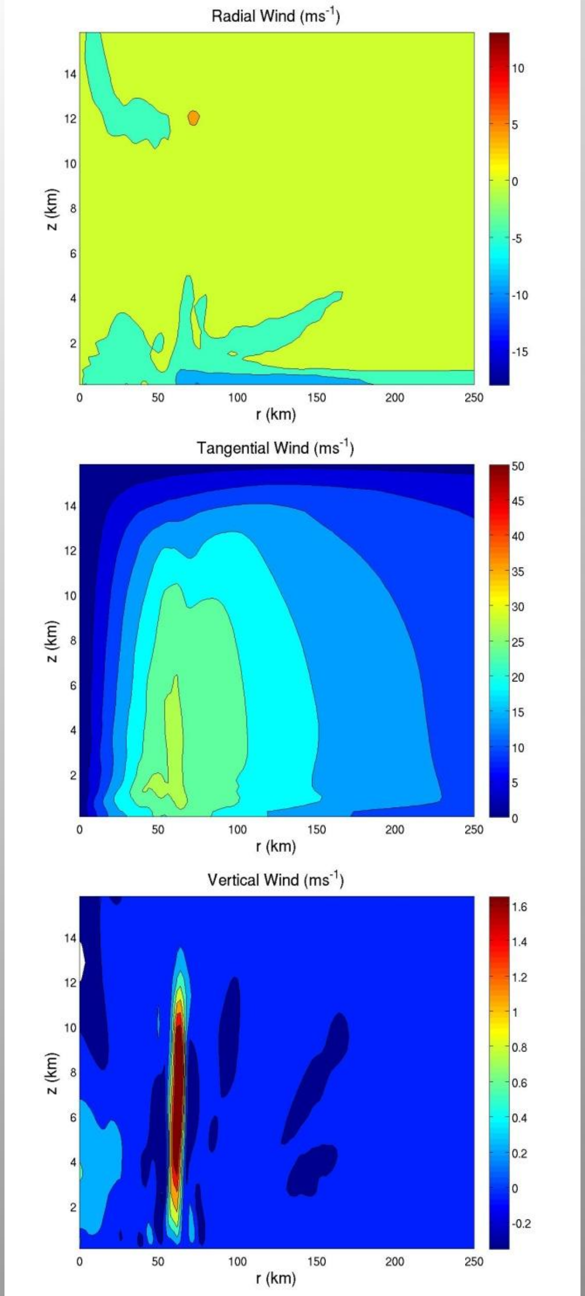
# Willoughby (SC) vs. Willoughby (No SC) – Hour 4

*U*

*V*

*W*



# Willoughby (SC) vs. Willoughby (No SC) – Hour 6

*U*

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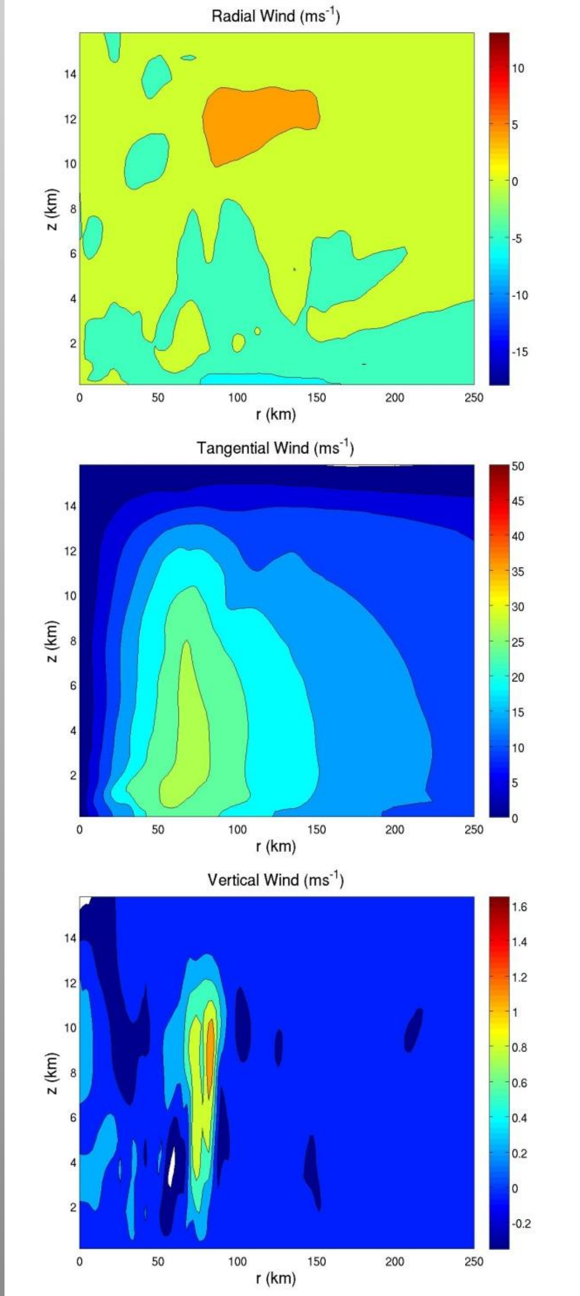


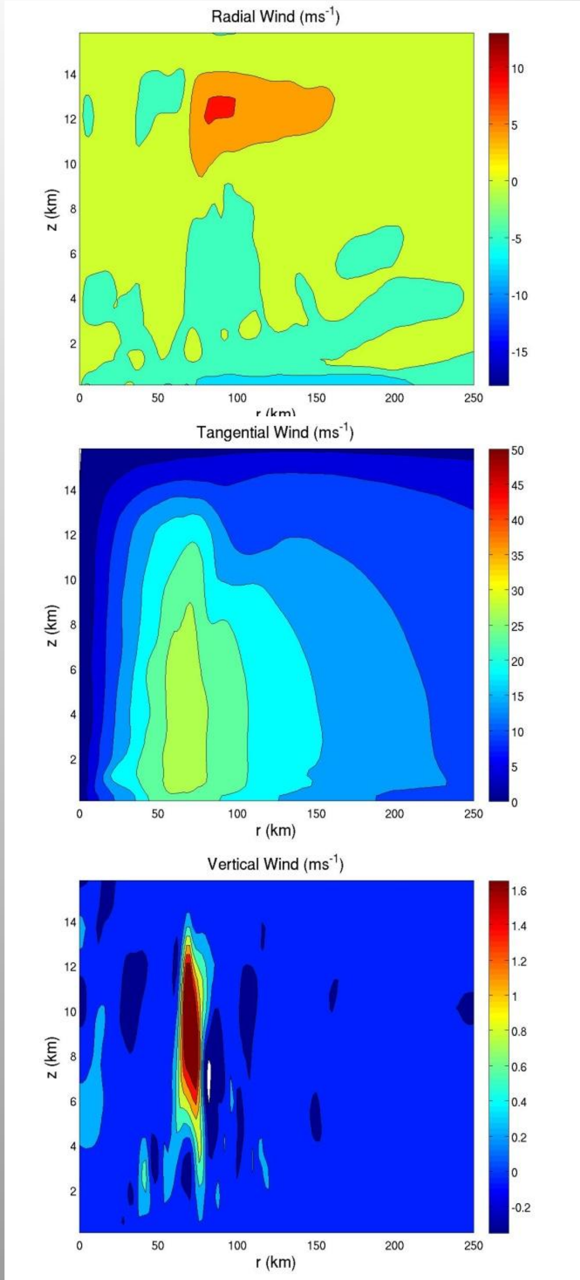

# Willoughby (SC) vs. Willoughby (No SC) – Hour 12

*U*

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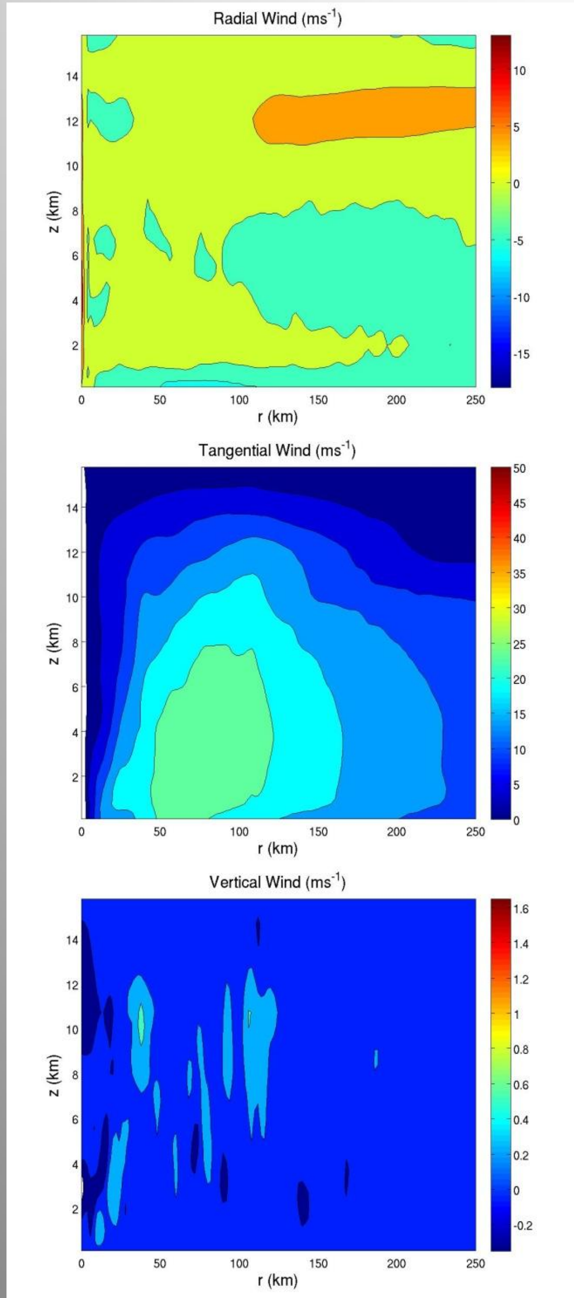


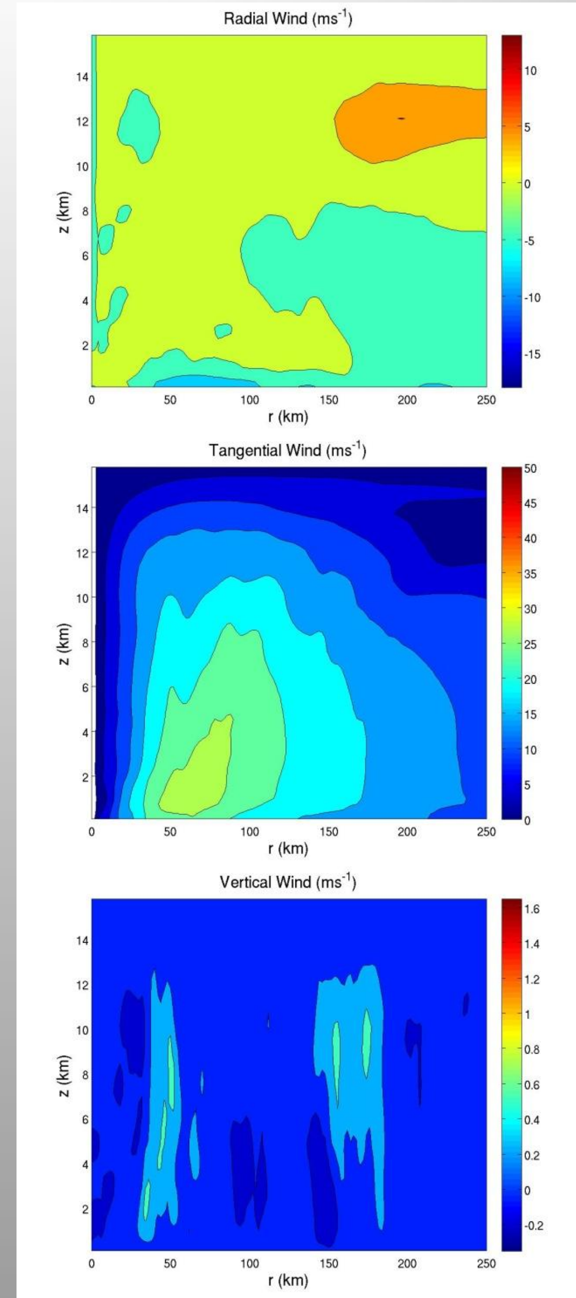

# Willoughby (SC) vs. Willoughby (No SC) – Hour 24

*U*

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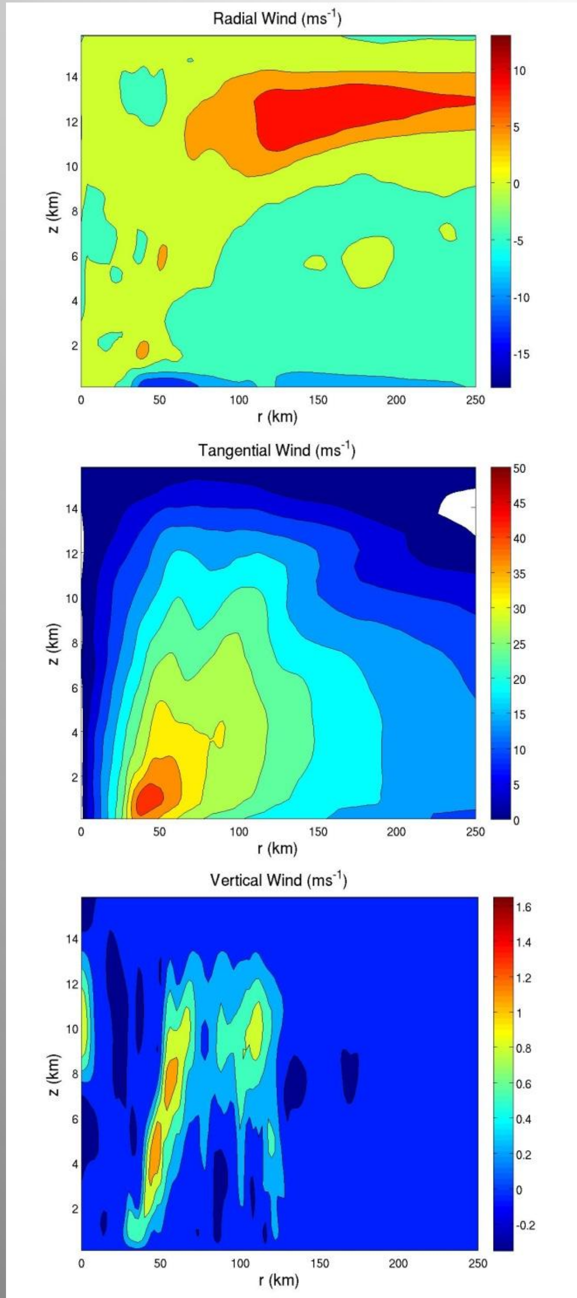
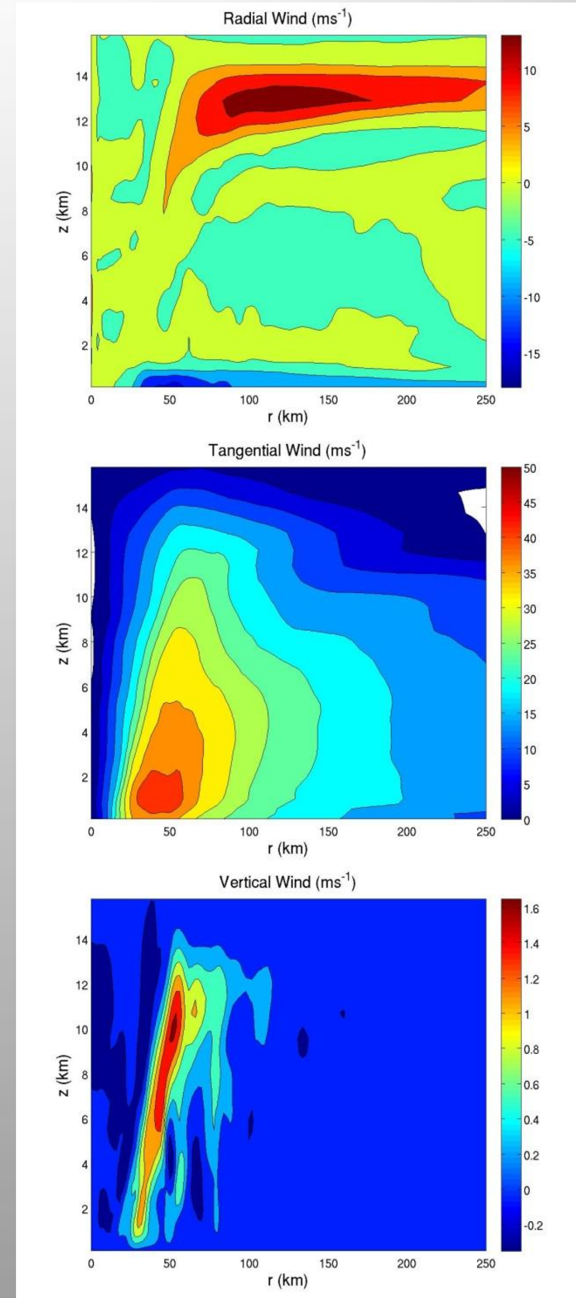
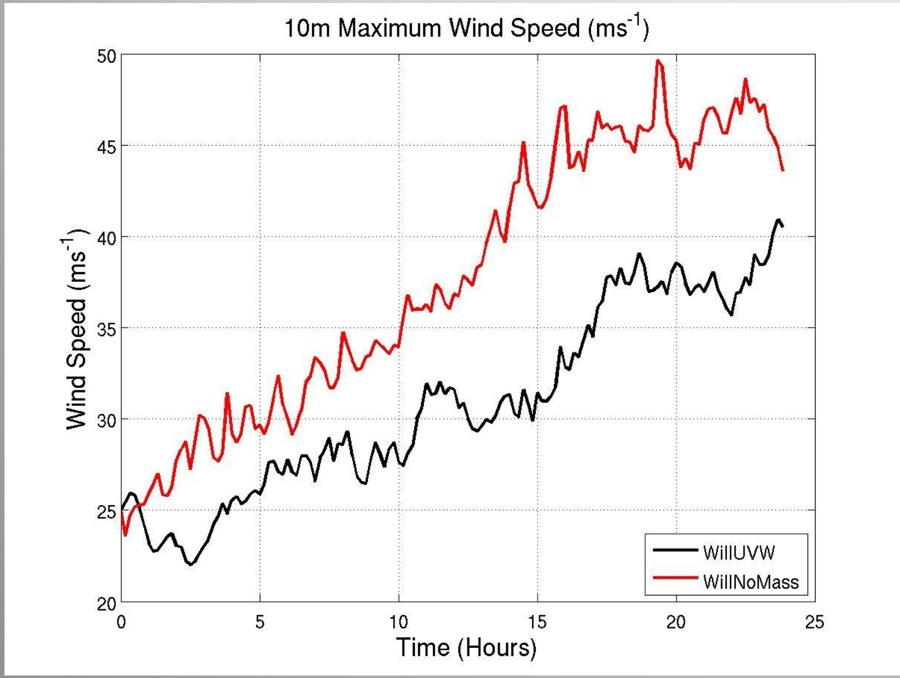
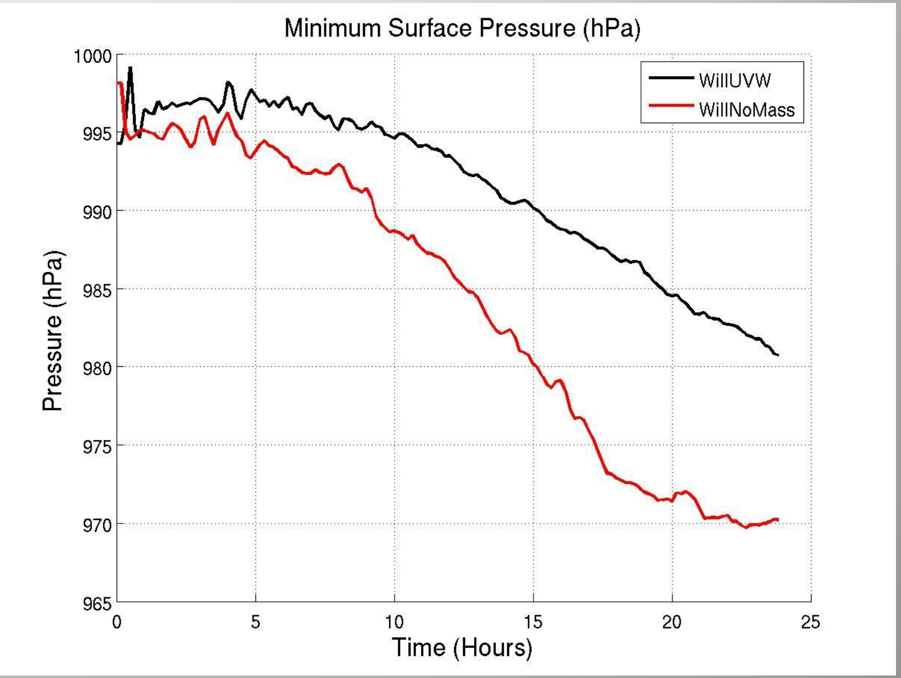
*W*



# Willoughby (SC) vs Willoughby (SC-No Mass Pert.)



# Willoughby (SC) vs. Willoughby (SC-NoMass) – Hour 2

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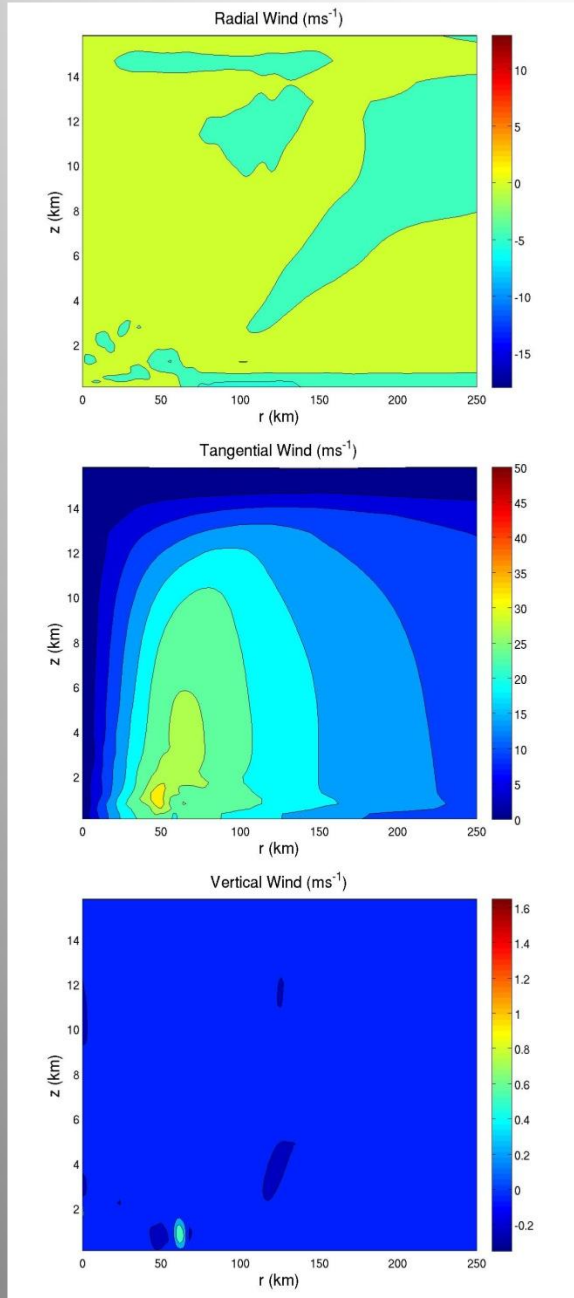


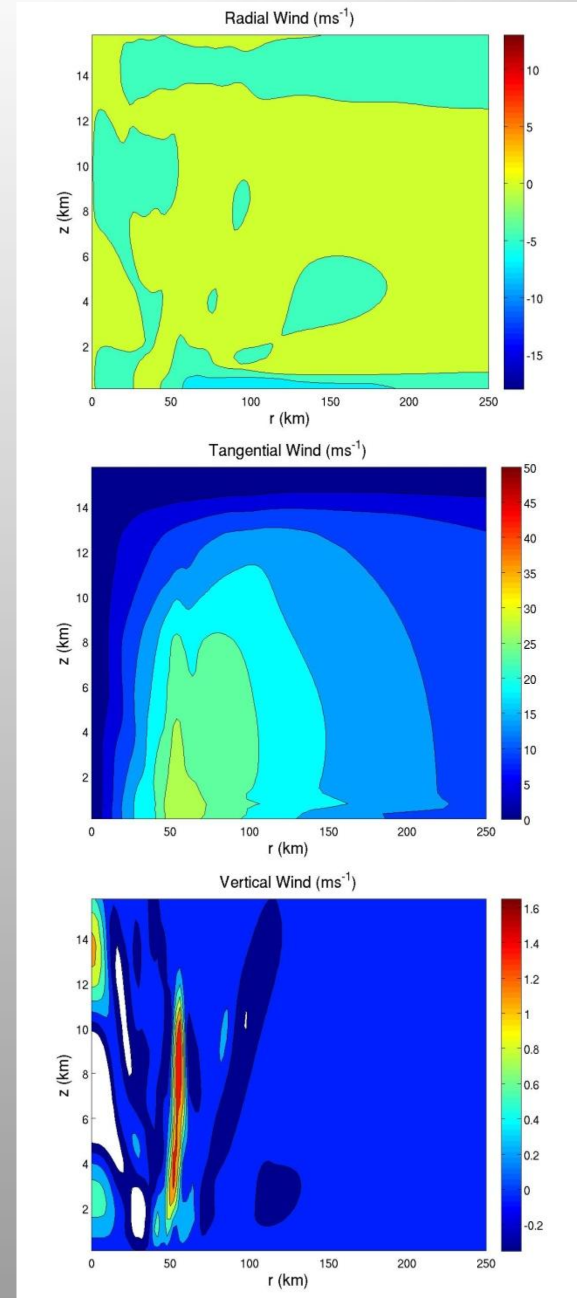

# Willoughby (SC) vs. Willoughby (SC-NoMass) – Hour 4

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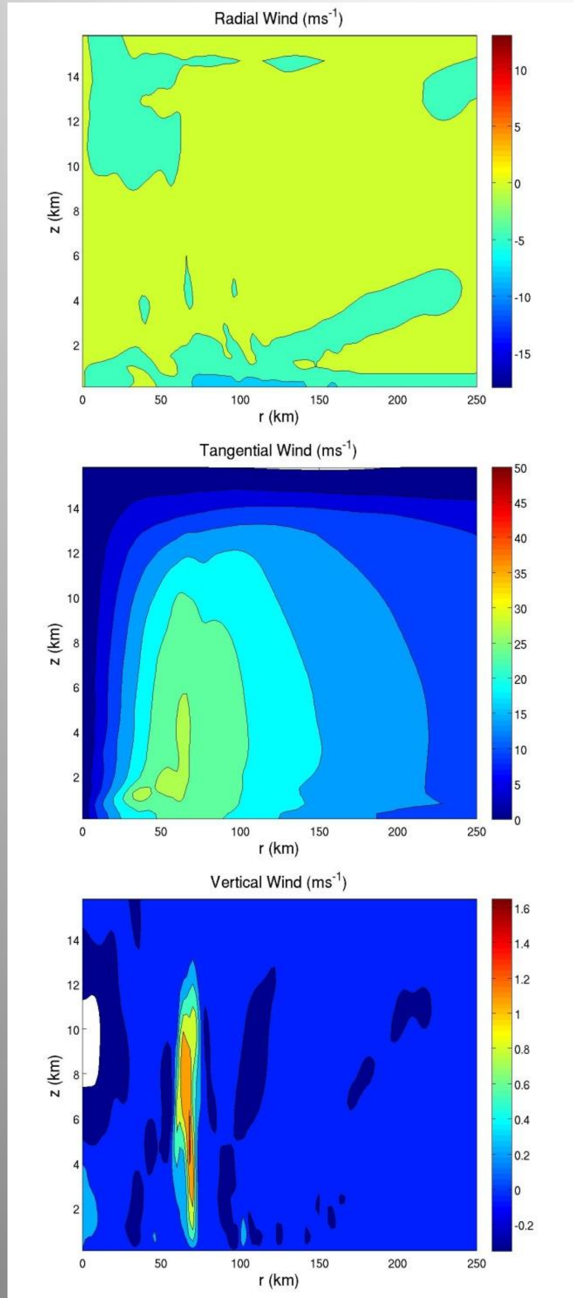


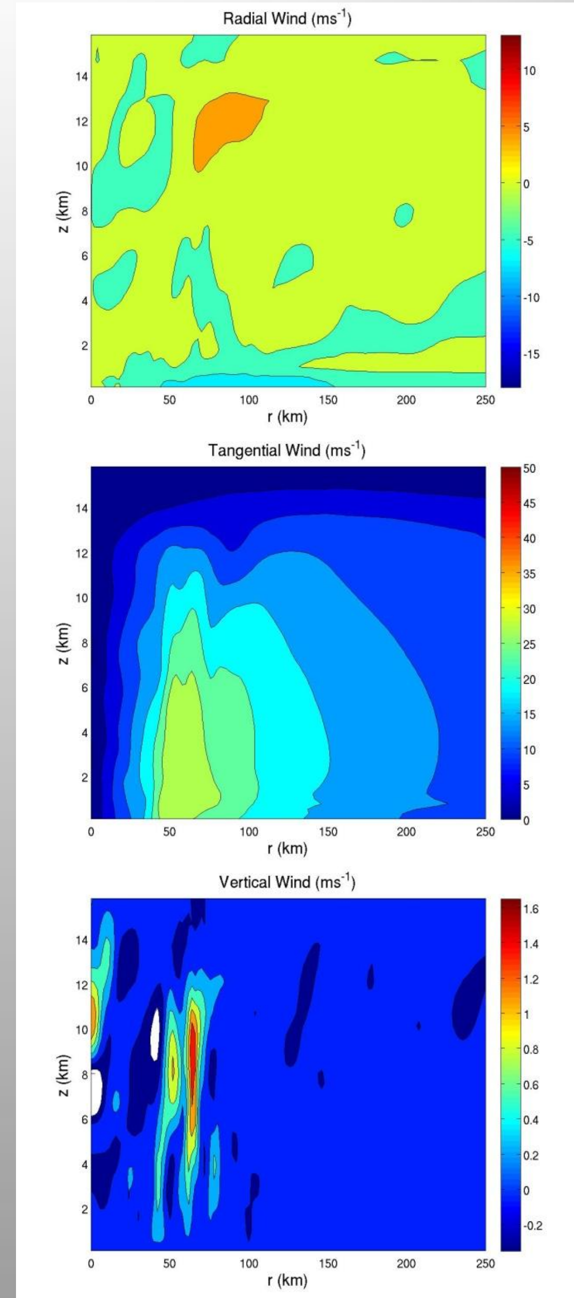

# Willoughby (SC) vs. Willoughby (SC-NoMass) – Hour 6

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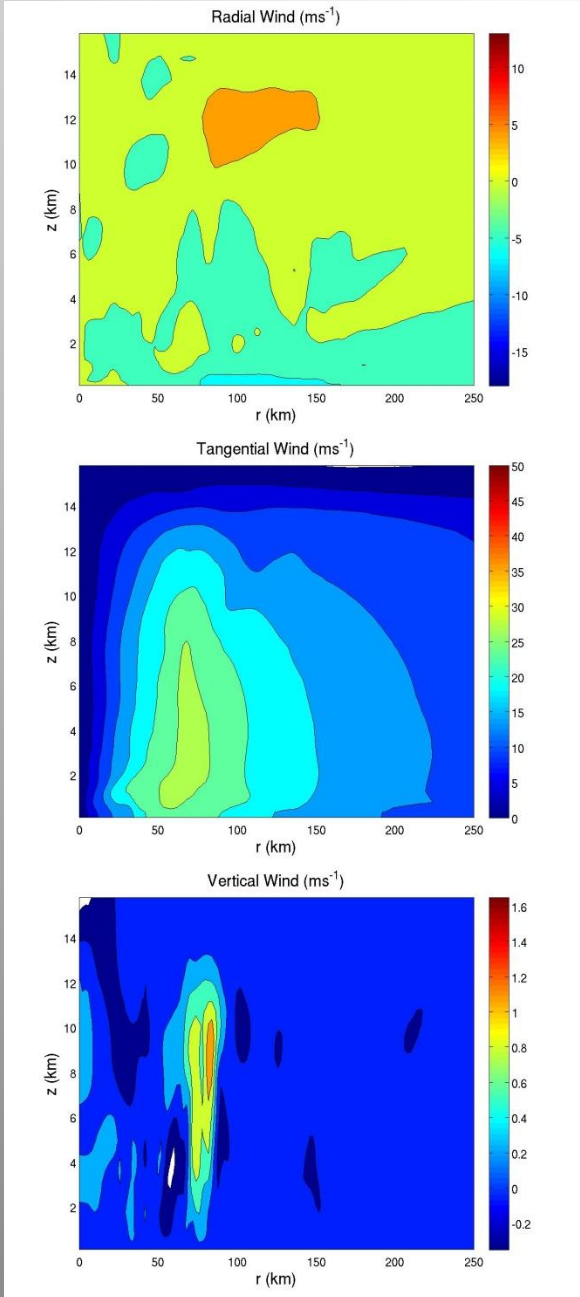


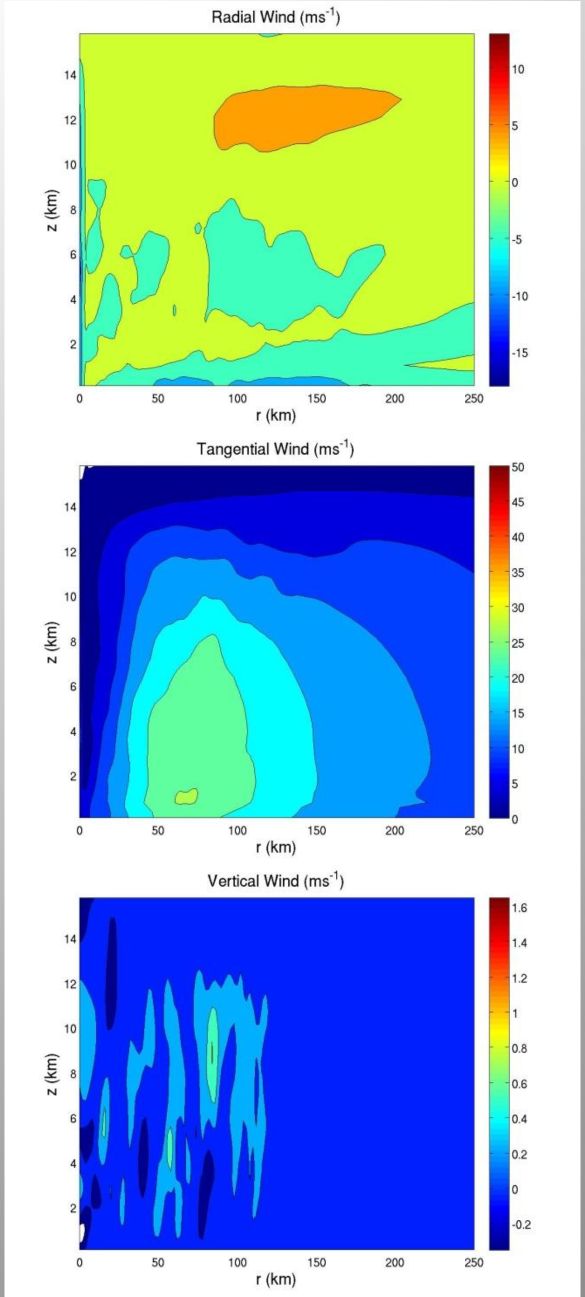

# Willoughby (SC) vs. Willoughby (SC-NoMass) – Hour 12

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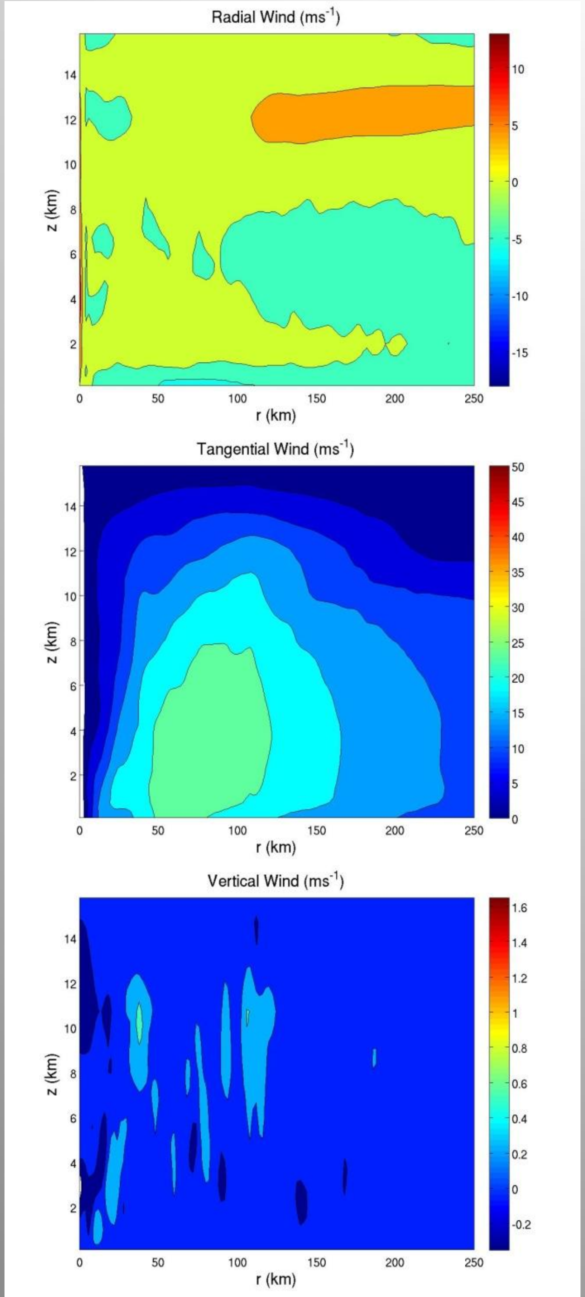


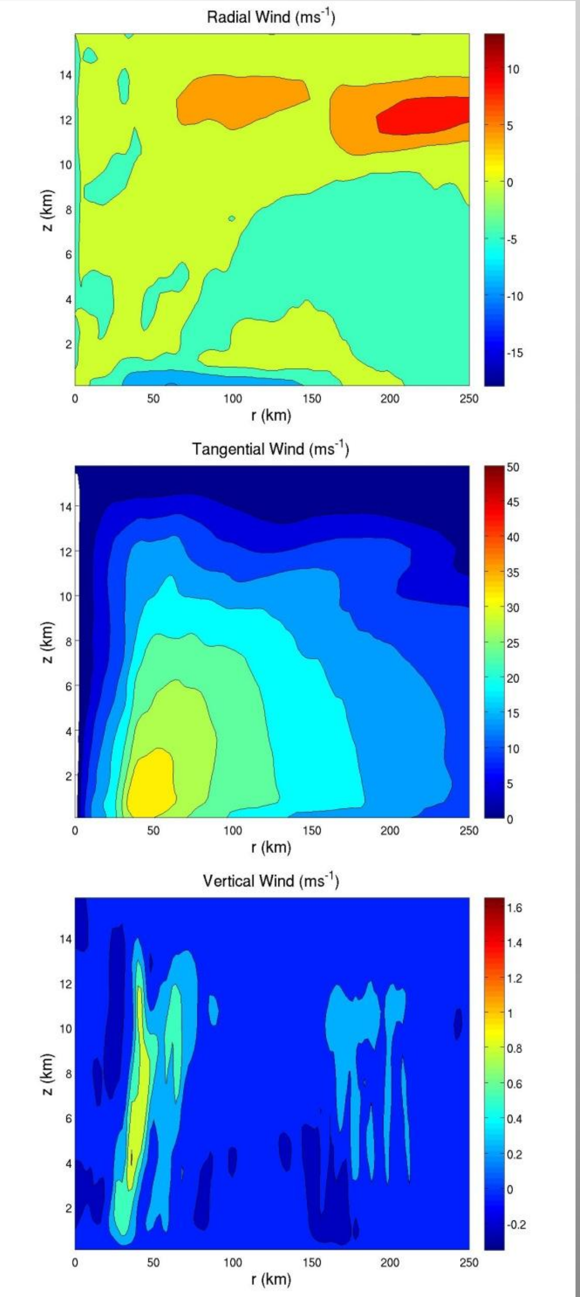

# Willoughby (SC) vs. Willoughby (SC-NoMass) – Hour 24

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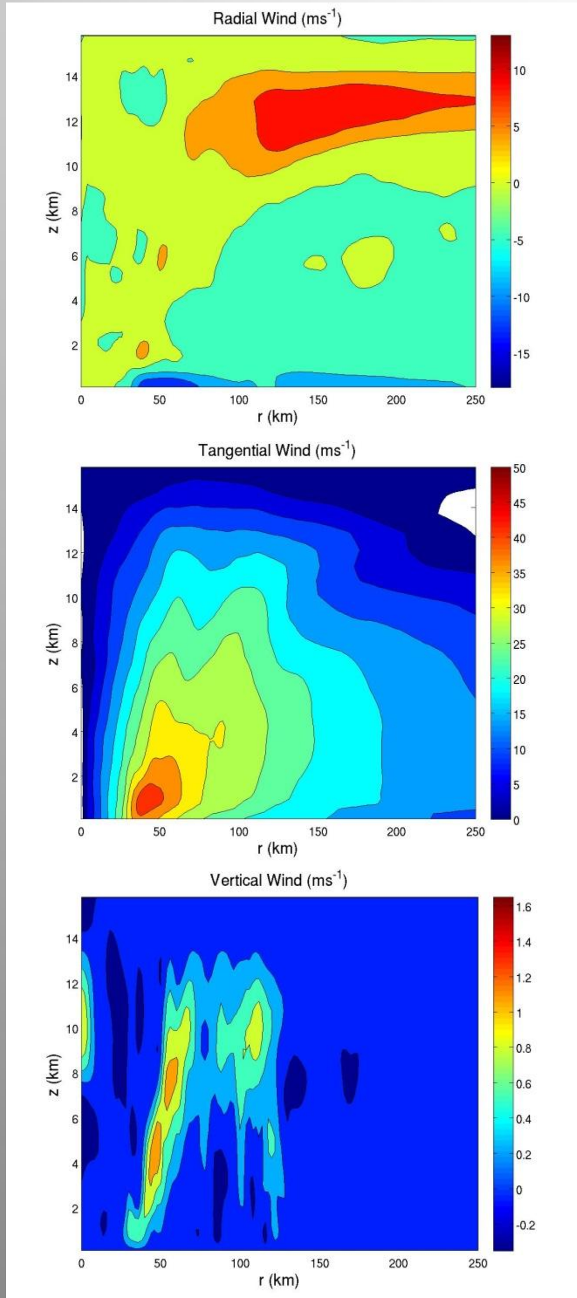


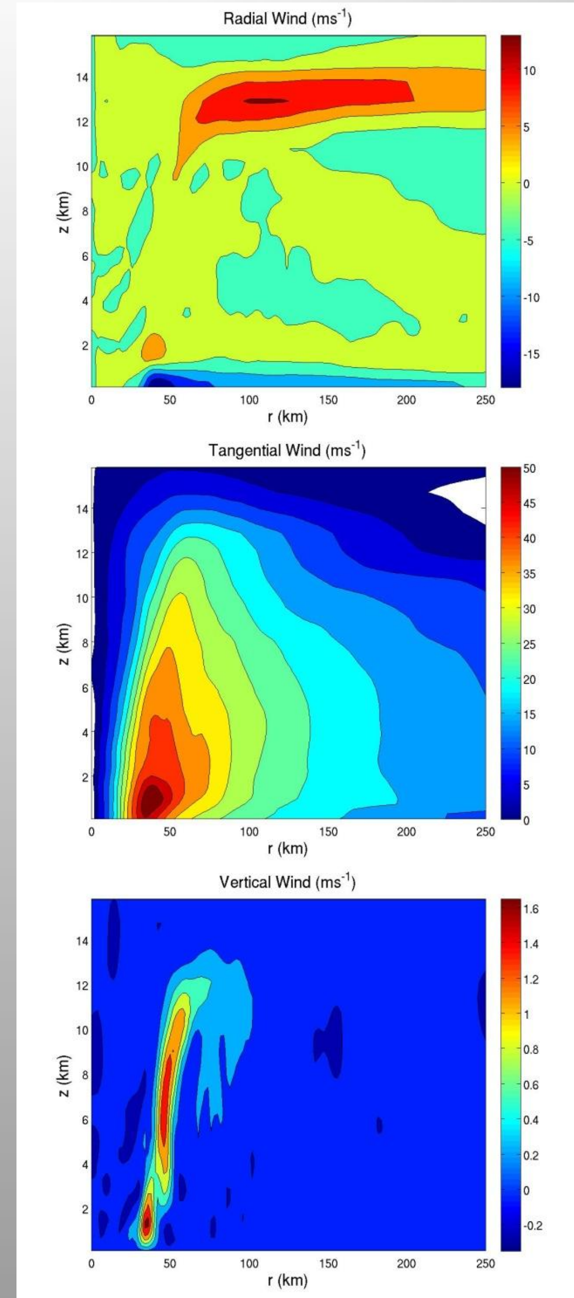

# Conclusions

- A highly configurable vortex initialization methodology has been constructed that allows precision manipulation of the initial vortex structure.
- The configuration options range from the highly simplistic to the highly complex in which a continuous boundary layer/free atmosphere vortex flow with a mass conserving secondary circulation may be implemented.
- Several test cases show that initial spin-down of the vortex, from a structural perspective, is reduced when the full three dimensional wind field is accounted for.