

# Vortex Initialization of the Atmospheric Model in HWRF

Hurricane Tutorial

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# Outline

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3. Bogus storm
4. Storm relocation
5. Storm size correction
6. Storm intensity correction
7. Summary and discussions

# 1. Overview

- **HWRF initialization**

- Mini analysis for background vortex + GSI (3D VAR)**

- **The mini analysis is to create a better background fields, and includes three parts:**

- 1) storm relocation** (data: storm center position)

- 2) storm size correction** (data: radius of maximum surface wind speed, and radius of the outermost closed isobar or average radius of 34 knots wind speed)

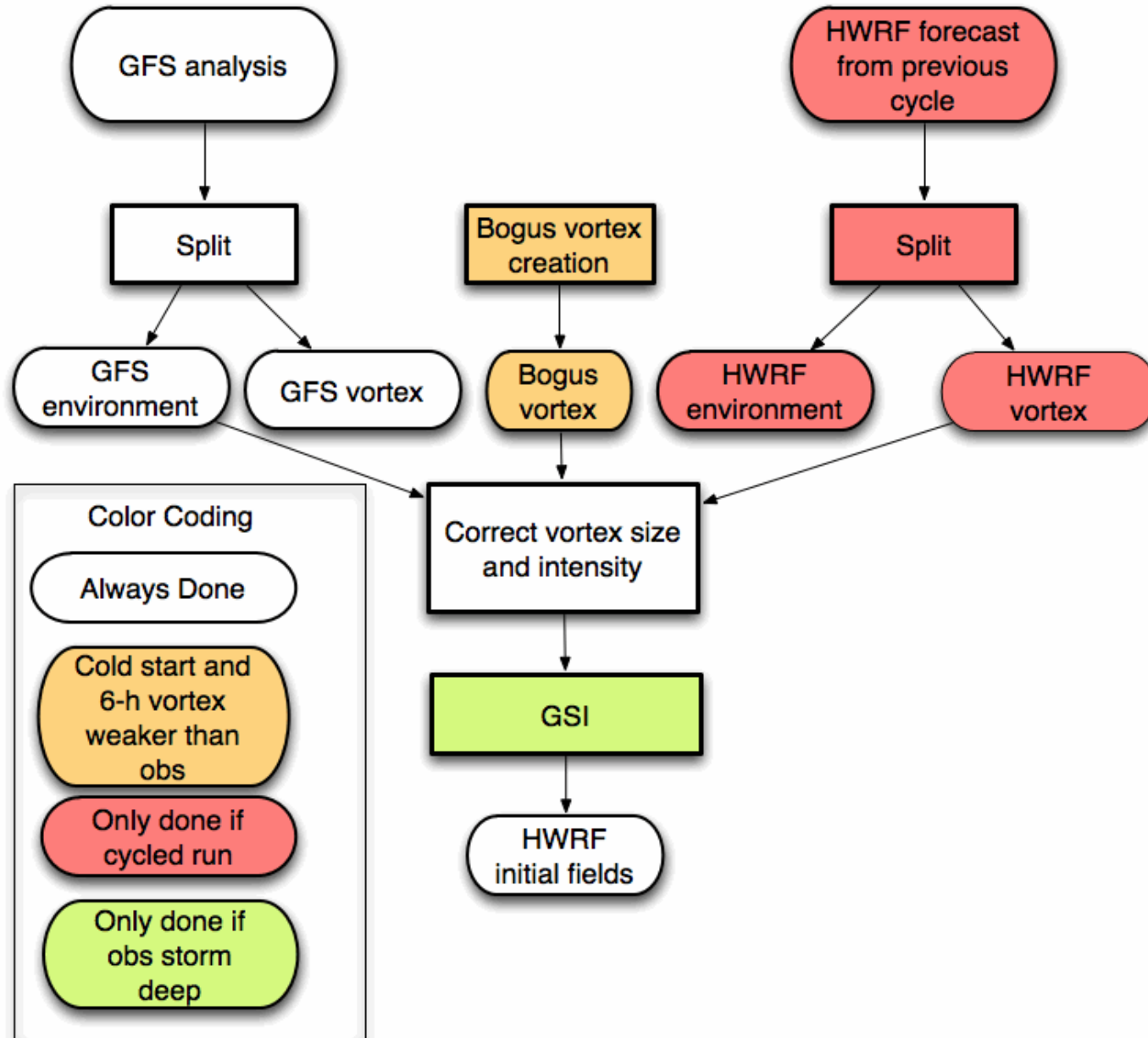
- 3) storm intensity correction** (data: maximum surface wind speed, to some extent, minimum surface pressure).

- **Important for model consistent formulation:**

- if vortex location, size and intensity in background are close to observations: all corrections are small.

- If they match the observations: no changes to the background fields

# HWRF Operational Initialization



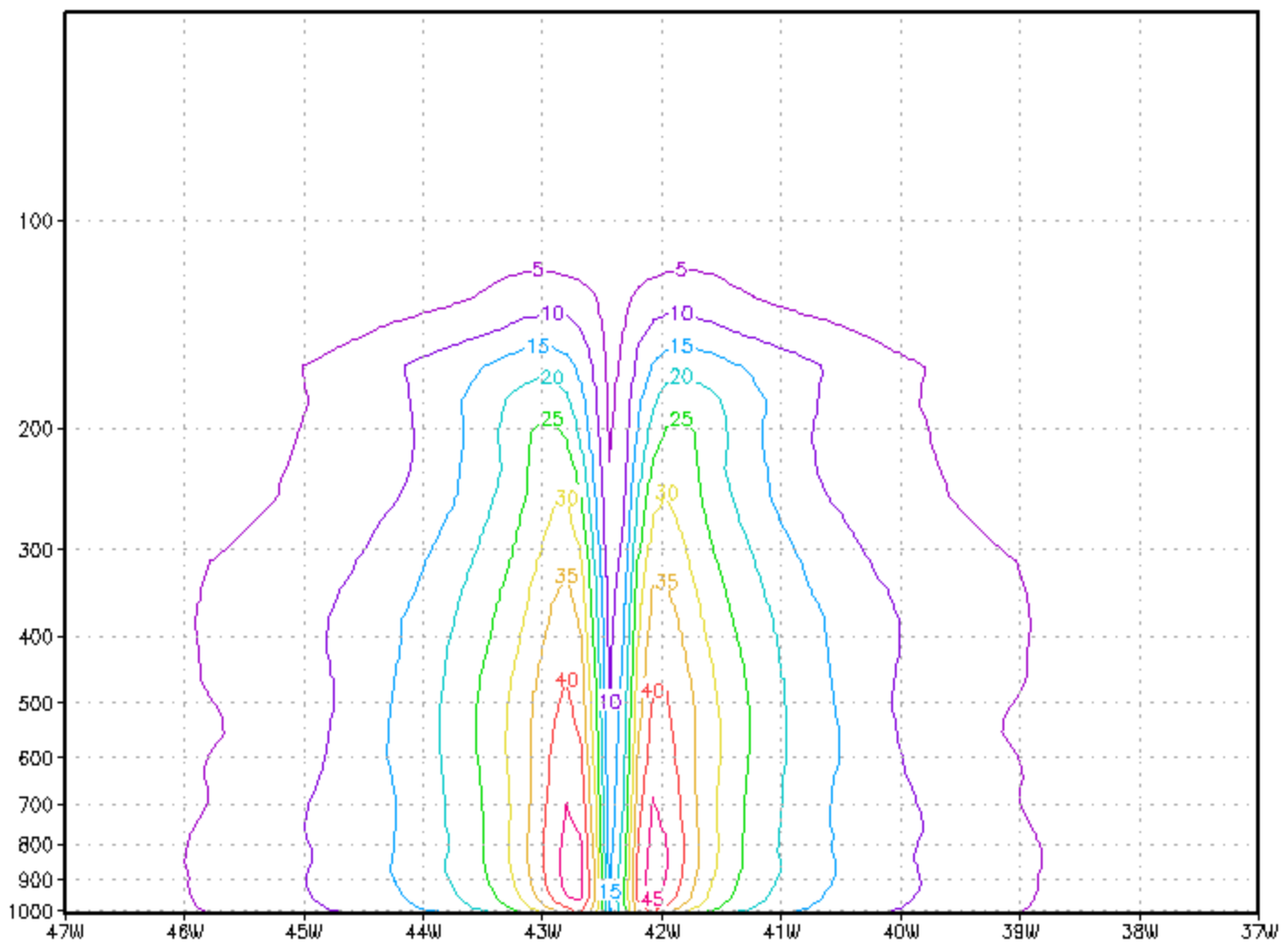
### 3. Bogus vortex

- No previous 6-h model forecast or maximum observed wind speed less than 12m/s
  - Bogus storm is used (cold start)
- Storms in model are weaker than obs.
  - Bogus vortex is used to correct storm intensity
- User does not need to create the following 2D composite vortex, it is pre-generated.
- Creation of 2D composite vortex (or synthetic vortex)
  - Choose a strong storm (over ocean) with small size and good axi-symmetric structure from an old model forecast
  - Separate the storm from its environment
  - Calculate the 2D axi-symmetric vortex of the storm. The 2D vortex has hurricane perturbations  $U$ ,  $V$ ,  $T$ ,  $r$  (water vapor mixing ratio) and  $P_s$

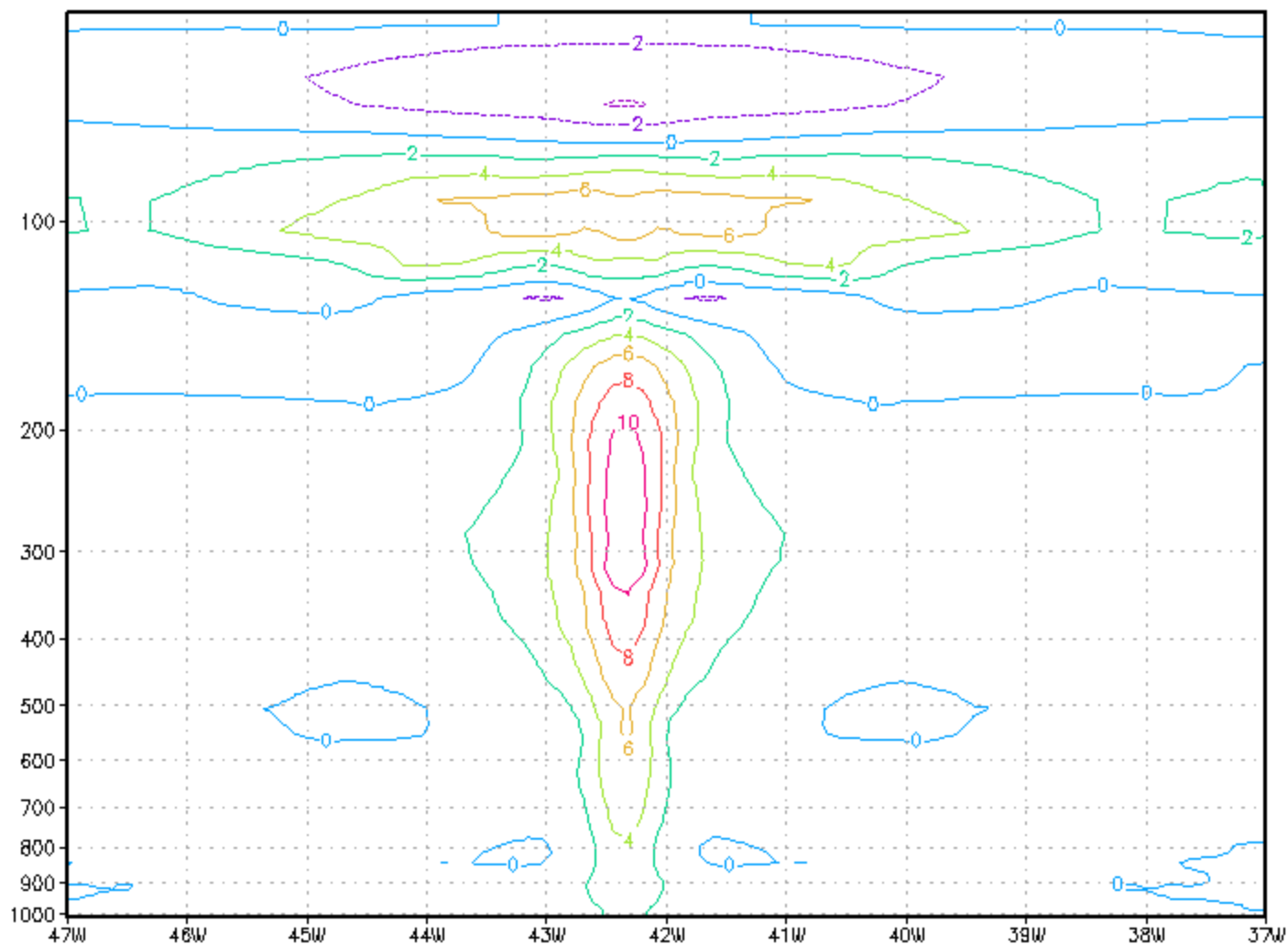
## Bogus vortex (continue)

- The 2D composite vortex should be recreated whenever the changes of model physics strongly affect the storm structures
- Creation of the bogus vortex
  - Horizontally smooth the 2D storm profiles (U, V, T, r and Ps, note: Ps is 1D) until the radius of maximum wind or the maximum wind speed of the 2D vortex is close to the observation.
- The bogus vortex will be treated similar to the 6-h model forecasted vortex, and will go through size and intensity corrections to match the observation values

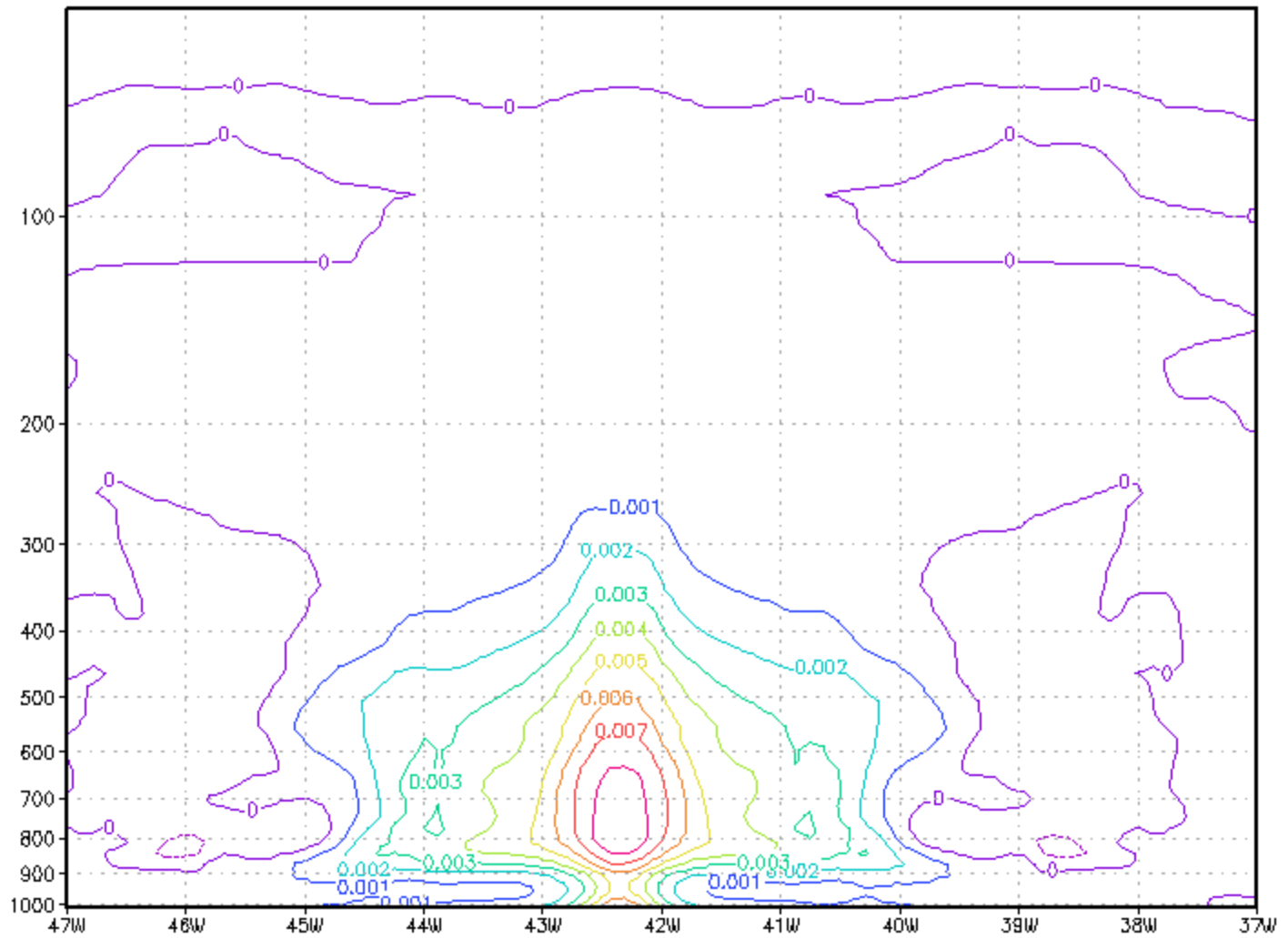
# Total Wind Speed (m/s) in Composite Storm



# Temperature Pert in Composite Storm



# Mixing Ratio Pert in Composite Storm



## 4. Vortex relocation

- **GFS (Liu et al., 2000)**

A vortex relocation procedure to initialize hurricanes was implemented in GFS in year 2000. The relocation procedure takes the guess field and moves the hurricane vortex to the correct location before the GSI updates the analysis.

The steps can be briefly summarized as follows:

- 1) locate the hurricane vortex center in the guess field,
- 2) separate hurricane model's vortex from its environmental field,
- 3) move the hurricane vortex to the TPC's official position, and
- 4) if the vortex is too weak in the guess field, add a bogus vortex in the GSI analysis\*

\* *this step is not done in HWRF*

## 4. Vortex relocation

- **GFS (Liu et al., 2000)**
  - 31% improvement in track forecasts from GFS
  - 25% improvement from GFDL model
- **GFS Ensemble (Liu et al. 2006b)**
  - Reduce the spreads of storm track and storm intensity forecasts
- **COAMPS-TC (Liou, 2008, personal communication)**
- **ARW (Hsiao et al., MWR, 2009)**
  - 28%-50% improvements in track forecasts

# 5. Storm Size Correction

- Observation data used from TC vitals for the eyewall and storm size corrections are:
  - radius of maximum wind speed
  - radius of outmost closed isobar
  - radius of 34 knots wind (for strong storms)

We use this information to correct the size of the composite storm, as well as the storm produced from the 6-h model forecast by stretching or compressing the model grid.

## Storm Size Correction (continue)

- Stretch/compress the model grid

$$\alpha_i = \frac{\Delta r_i^*}{\Delta r_i} = a + br_i \quad (1.4.1.1)$$

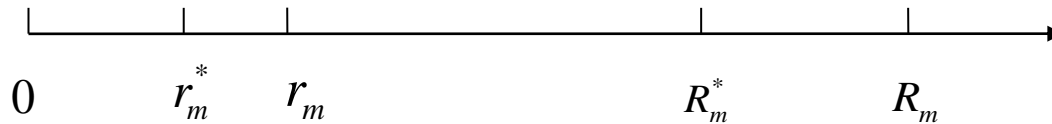
Integrate equation (4.1.1), we have

$$r^* = f(r) = ar + \frac{1}{2}br^2 \quad (1.4.1.2)$$

Where  $a$  and  $b$  are constants,  $r$  and  $r^*$  are the distances from the storm center before and after the model grid is stretched

## Storm Size Correction (continue)

- Data used:
  - Radius of the maximum wind speed ( $r_m$  and  $r_m^*$ )
  - Radius of the outmost closed isobar ( $R_m$  and  $R_m^*$ )
    - Model data:  $r_m, R_m$
    - Observation data:  $r_m^*, R_m^*$



- We compress/stretch the model grids such that

$$\text{At } r = r_m, \quad r^* = f(r_m) = r_m^* \quad (1.4.1.3)$$

$$\text{At } r = R_m, \quad r^* = f(R_m) = R_m^* \quad (1.4.1.4)$$

## Storm Size Correction (continue)

- Substituting (1.4.1.3) and (1.4.1.4) into (1.4.1.2),

$$ar_m + \frac{1}{2}br_m^2 = r_m^* \quad (1.4.1.5)$$

$$aR_m + \frac{1}{2}bR_m^2 = R_m^* \quad (1.4.1.6)$$

- Solve equations (1.4.1.5) and (1.4.1.6), we have

$$a = \frac{r_m^* R_m^2 - r_m^2 R_m^*}{R_m r_m (R_m - r_m)} \quad b = 2 \frac{R_m^* r_m - R_m r_m^*}{R_m r_m (R_m - r_m)} \quad (1.4.1.7)$$

## Storm Size Correction (continue)

- **Define the radius of outmost closed isobar from model output**

As discussed in 2010 DTC hurricane scientific document, the minimum surface pressure need to be scaled to observation value before calculating the radius of outmost isobar, we define,

for 6-h HWRF vortex (vortex #1),

$$f_1 = \frac{\Delta p_1}{\Delta p_{1c}} \Delta p_{obs}$$

for composite storm (vortex #2),

$$f_2 = \frac{\Delta p_2}{\Delta p_{2c}} \Delta p_{obs}$$

Where  $\Delta p_1$  and  $\Delta p_2$  are the 2D perturbation pressures for vortex #1 and vortex #2, respectively.  $\Delta p_{1c}$  and  $\Delta p_{2c}$  are the minimum values form  $\Delta p_1$  and  $\Delta p_2$ .  $\Delta p_{obs}$  is the observed minimum perturbation pressure.

## Storm Size Correction (continue)

- **Define radius of outmost closed isobar from model output (continue)**

The radius of outmost closed isobar for vortex #1 and vortex #2 can be defined as the radius of the 1mb contour from  $f_1$  and  $f_2$ , respectively.

We can show that after storm size correction for vortex #1 and vortex #2, the radius of outmost closed isobar is unchanged for any combination of the vortex #1 and vortex #2. For example,

$$\Delta p_1 + \beta \Delta p_2 = \frac{\Delta p_1}{\Delta p_{1c}} \Delta p_{1c} + \beta \frac{\Delta p_2}{\Delta p_{2c}} \Delta p_{2c}$$

at 1mb contour, we have  $f_1 = 1$  and  $f_2 = 1$ , or

$$\frac{\Delta p_1}{\Delta p_{1c}} = \frac{\Delta p_2}{\Delta p_{2c}} = \frac{1}{\Delta p_{obs}}$$

so,

$$\Delta p_1 + \beta \Delta p_2 = \frac{\Delta p_1}{\Delta p_{1c}} \Delta p_{1c} + \beta \frac{\Delta p_2}{\Delta p_{2c}} \Delta p_{2c} = \frac{1}{\Delta p_{obs}} (\Delta p_{1c} + \beta \Delta p_{2c}) = 1$$

## Storm Size Correction (continue)

- **Define the radius of 34 knots wind**

Similar to the calculation of the radius of the outmost closed isobar, we need to scale the max wind speed for vortex #1 and vortex #2 before calculating the radius of 34 knot wind. We define, for 6-h HWRF vortex (vortex #1),

$$g_1 = \frac{v_1}{v_{1m}} (v_{obs} - \bar{v}_m)$$

for composite storm (vortex #2),

$$g_2 = \frac{v_2}{v_{2m}} (v_{obs} - \bar{v}_m)$$

Where  $v_{1m}$  and  $v_{2m}$  are the maximum wind speed for vortex #1 and vortex #2, respectively, and  $(v_{obs} - \bar{v}_m)$  is the observed maximum wind speed subtract the environment wind. The environment wind is defined as

$$\bar{v}_m = \max(0, U_{1m} - v_{1m})$$

where  $U_{1m}$  is the max wind speed at 6h forecast

## Storm Size Correction (continue)

- **Define the radius of 34 knots wind (continue)**

The radius of 34 knot wind for vortex #1 and vortex #2 are calculated as the radius by setting  $g_1$  and  $g_2$  to be 34 knot, respectively.

The combination of vortex #1 and vortex #2 can be written as

$$v_1 + \beta v_2 = \frac{v_1}{v_{1m}} v_{1m} + \beta \frac{v_2}{v_{2m}} v_{2m}$$

At 34 knot radius, we have ( $g_1=34, g_2=34$ )

$$v_1 + \beta v_2 = \frac{v_1}{v_{1m}} v_{1m} + \beta \frac{v_2}{v_{2m}} v_{2m} = \frac{34}{v_{obs} - \bar{v}_m} (v_{1m} + \beta v_{2m}) = 34$$

Note we have used,

$$(v_{1m} + \beta v_{2m}) + \bar{v}_m = v_{obs}$$

## Storm Size Correction (continue)

- In 2010 operational HWRF, only radius of the maximum wind speed is used for storm size correction, and  $\alpha_i$  is set to be constant ( $b=0$ ).

We limit the correction to be 15% of the model value ( $0.85 < \alpha_i < 1.15$ ), and

$$\alpha_i = a = r_m^* / r_m = R_m^* / R_m \quad (1.4.1.12)$$

In 2011 HWRF, Kevin Yeh (HRD) added the second parameter in the storm size correction according to equation (1.4.1.7)

## Storm Size Correction (continue)

- Sea-level pressure adjustment

$$\Delta p^* = \Delta p \frac{\psi^*}{\psi} = \Delta p \cdot \Gamma \quad (1.4.1.1.9)$$

where,

$$\psi^* = \int_{\infty}^{r^*} \left( \frac{v^2}{r^* f_0} + v \right) dr^* \quad (1.4.1.1.6)$$

And

$$\psi = \int_{\infty}^{r^*} \frac{1}{\alpha(r^*)} \left[ \frac{v^2}{r^*} \frac{f(r^*)}{r(r^*) f_0} + v(r^*) \right] dr^* \quad (1.4.1.1.4)$$

## Storm Size Correction (continue)

- Temperature adjustment

Temperature adjustment is proportional to the magnitude of the vortex temperature perturbation,

$$T^* = T_e + \Gamma \Delta T = T + (\Gamma - 1) \Delta T \quad (1.4.1.2.6)$$

## Storm Size Correction (continue)

- Water vapor adjustment

Assumption: relative humidity is unchanged before and after the temperature correction, we have

$$q^* \approx \frac{e^*}{e} q \approx \frac{e_s^*}{e_s} q \approx q + \left(\frac{e_s^*}{e_s} - 1\right)q \quad (1.4.1.3.4)$$

and

$$\frac{e_s^*}{e_s} = \exp\left[\frac{17.67 * 243.5(T^* - T)}{(T^* - 29.66)(T - 29.66)}\right] \quad (1.4.1.3.6)$$

## Storm Size Correction (continue)

- Convergence

If  $\alpha=1.0$ , no storm size correction, we have

$$\Gamma(r^*) = \psi^* / \psi = 1.0$$

from equations (1.4.1.1.9), (1.4.1.2.6) and (1.4.1.3.6), there will be no adjustments in 2D sea-level pressure, 3D temperature and 3D water vapor fields in the background

# 6. Storm Intensity Correction

- Wind speed correction

- Denotes  $u_1$  and  $v_1$  as the background horizontal velocity, and  $u_2$  and  $v_2$  as the vortex horizontal velocity
- Define two functions

$$F_1 = \sqrt{(u_1 + u_2)^2 + (v_1 + v_2)^2} \quad (1.4.2.1.1)$$

$$F_2 = \sqrt{(u_1 + \beta u_2)^2 + (v_1 + \beta v_2)^2} \quad (1.4.2.1.2)$$

$F_1$  is the 3D wind speed if we simply add a vortex to the background fields, and  $F_2$  is the new wind speed after intensity correction.

- To find  $\beta$ , assume that the maximum wind speed for  $F_1$  and  $F_2$  are at the same model grid point.
  - First find the model grid point  $m$  where  $F_1$  is at its maximum (denotes the wind components as  $u_1^m$ ,  $v_1^m$ ,  $u_2^m$ , and  $v_2^m$ ).
  - At model grid  $m$ , let  $F_2 = v_{obs}$ , then solve the equation to obtain  $\beta$ .

## Storm Intensity Correction (continue)

- New initial 3D wind fields

$$u(x, y, z) = u_1(x, y, z) + \beta u_2(x, y, z)$$

$$v(x, y, z) = v_1(x, y, z) + \beta v_2(x, y, z)$$

And

$$\beta = \frac{(-u_1^m u_2^m - v_1^m v_2^m + \sqrt{v_{obs}^2 (u_2^{m2} + v_2^{m2}) - (u_1^m v_2^m - v_1^m u_2^m)^2}}{(u_2^{m2} + v_2^{m2})}$$

(1.4.2.1.4)

where  $v_{obs}$  is the maximum 10m observed wind converted to the first model level.

## Storm Intensity Correction (continue)

- We consider two cases in the following discussion

### ➔ Case I: wind speed in background is stronger than obs.

- The background fields are the same as the HWRF (or GFS) environment fields (no vortex).
- We correct the intensity of vortex #1 (6h HWRF model vortex) before adding it to the background fields

### ➔ Case II: wind speed in background is weaker than obs.

- First, we add back the 6-h HWRF model vortex to the GFS environment fields (after relocation and storm size correction)
- Correct the intensity of vortex #2 (axi-symmetric vortex) before adding it to the new background fields.

Note: Vortex #2 has the same radius of the maximum wind speed and radius of outmost closed isobar (or radius of 34 knot wind) as vortex #1

## Storm Intensity Correction (continue)

- Sea-level pressure adjustment after wind speed correction
  - Case I: wind speed in background is stronger than obs.
    - If the background vortex is close to observation, we have,

$\beta$  is close to 1

And the pressure adjustment is

$$\Delta p^{new} = \Delta p \frac{\psi^{new}}{\psi} \frac{\Delta p_{obs}}{\Delta p_c} \quad (1.4.2.2.5)$$

Where  $\Delta p_{obs} = p_{obs} - p_{ec}$ , and  $p_{ec}$  is the environment field at storm center.  $\Delta p = p_m - p_e$ , and  $\Delta p_c$  is the value of  $\Delta p$  at the storm center, and

$$\psi = \int_{\infty}^r \left( \frac{v_1^2}{rf_0} + v_1 \right) dr \quad (1.4.2.2.2)$$

$$\psi^{new} = \int_{\infty}^r \left[ \frac{(\beta v_1)^2}{rf_0} + \beta v_1 \right] dr \quad (1.4.2.2.3)$$

## Storm Intensity Correction (continue)

- Sea-level pressure adjustment after wind speed correction
  - Case II: wind speed in background is weaker than obs.

- Since the background vortex is already added back, we have,

$\beta$  is close to 0

and the pressure adjustment

$$\Delta p^{new} \approx \Delta p_1 + \frac{\Delta p_2}{\Delta p_{2c}} (\Delta p_{obs} - \Delta p_{1c}) \quad (1.4.2.2.12)$$

Where  $\Delta p_{1c}$  and  $\Delta p_{2c}$  are the minimum perturbation pressures at the vortex center for vortex #1 and vortex #2, respectively, and  $\Delta p_{obs}$  is the observed minimum surface pressure subtract the GFS environment sea-level pressure at the storm center.

- model consistent pressure adjustment is discussed next

## Storm Intensity Correction (continue)

- Sea-level pressure adjustment after wind speed correction
  - Model consistent sea-level pressure adjustment
    - instead of using the observed minimum surface pressure in equations (1.4.2.2.5) and (1.4.2.2.12), we use a newly modified minimum surface pressure based on the 6h model forecast (tracker output) and climatology.
    - Since the wind speed correction is small, we can assume the slope of the pressure-wind relationship in the model is close to the observed climatology value,

$$\frac{\partial p}{\partial v} = -0.1515(v)^{0.628} \quad (1.4.2.2.14)$$

And the new surface pressure used to replace the observed minimum surface pressure is,

$$p_m^* = p_m - 0.1515(v_{obs})^{0.628}(v_{obs} - v_m) \quad (1.4.2.2.15)$$

where  $v_m$  and  $p_m$  are the maximum surface wind and minimum surface pressure from the 6h model forecast (tracker output), respectively.

## Storm Intensity Correction (continue)

- Sea-level pressure adjustment after wind speed correction
  - Model consistent sea-level pressure adjustment:
    - In case I, equation (1.4.2.2.5) becomes,

$$\Delta p^{new} = \Delta p \frac{\psi^{new}}{\psi} \frac{\Delta p_m^*}{\Delta p_c} \quad (1.4.2.2.19)$$

- In case II, equation (1.4.2.2.12) becomes

$$\Delta p^{new} \approx \Delta p_1 + \frac{\Delta p_2}{\Delta p_{2c}} (\Delta p_m^* - \Delta p_{1c}) \quad (1.4.2.2.21)$$

Where  $\Delta p_m^* = p_m^* - p_{ec}$

## Storm Intensity Correction (continue)

- Temperature and water vapor adjustments after wind speed correction
  - Model consistent temperature adjustment:

Case I: wind speed in background is stronger than obs.

- If the background vortex is close to observation, we have,

$\beta$  is close to 1

- Define 
$$\Gamma = \frac{\psi^{new}}{\psi} \frac{\Delta p_m^*}{\Delta p_c}$$

Then temperature fields can be corrected using equation (1.4.1.2.6), and water vapor fields can be corrected following equations (1.4.1.3.4) and (1.4.1.3.6).

## Storm Intensity Correction (continue)

- Temperature and water vapor adjustments after wind speed correction
  - Model consistent temperature adjustment:

Case II: wind speed in background is weaker than obs.

- If the background vortex is close to observation, we have,

$\beta$  is close to 0

Define

$$\beta^* = \frac{\Delta p_m^* - \Delta p_{1c}}{\Delta p_{2c}}$$

then temperature adjustment becomes,

$$T^* = T_e + \Delta T_1 + \beta^* \Delta T_2 = T + \beta^* \Delta T_2 \quad (1.4.2.2.18)$$

- water vapor fields can be corrected using equations (1.4.1.3.4) and (1.4.1.3.6).

## Storm Intensity Correction (continue)

- Convergence for model consistent adjustment

➔ Case I: wind speed in background is stronger than obs.

If  $\beta=1.0$ , no wind speed correction, from equation (1.4.2.2.15) we have

$$\Delta p_m^* = \Delta p_c = p_m - p_{ec}$$

Therefore,

$$\Gamma(r) = \frac{\psi^{new}}{\psi} \frac{\Delta p_m^*}{\Delta p_c} = 1.0$$

from equations (1.4.2.2.5)\*, (1.4.1.2.6) and (1.4.1.3.6), there will be no adjustments in 2D sea-level pressure, 3D temperature and 3D water vapor fields in the background

## Storm Intensity Correction (continue)

- Convergence for model consistent adjustment

➔ Case II: wind speed in background is weaker than obs.

If  $\beta=0$ , no wind speed correction, from equation (1.4.2.2.15) we have

$$\Delta p_m^* = \Delta p_{1c} = p_m - p_{ec}$$

Therefore equation (1.4.2.2.12)\* becomes,

$$\Delta p^{new} = \Delta p_1$$

there will be no sea-level pressure correction. From equations (1.4.2.2.17)\*, (1.4.2.2.18) and (1.4.1.3.6), there will be no adjustments in 3D temperature and 3D water vapor fields in the background

# 7. Summary and discussions

- **Creation of the guess fields can be considered as a mini data analysis for storm vortex in the background fields which includes three parts:**
  - storm **relocation** (data used: storm center position)
  - storm **size** correction (data used: radius of maximum surface wind speed, and radius of the outermost closed isobar)
  - storm **intensity** correction (data used: maximum surface wind speed, and to some extent, the minimum sea level pressure)

**Note: Do storm size correction before storm intensity correction to avoid broad eyewall structure, or worse, two distinct eyewalls.**
- **If the background vortex is close to the observation, all corrections are small.**
  - From the convergence discussions, if the vortex location, vortex size and vortex intensity in the background fields match the observations, there will be no changes to any of the background fields

## Summary and discussions (continue)

- **More words about the HWRF initialization**

The purpose of the mini-analysis is to create better background fields using TC Vitals. Then add 3D data on top of the new vortex. Adding 3D data is difficult now since the eyewall structures produced by the model can be very different compared to observation. I give two examples here.

### 1) Radiance data in hurricane core area

HWRF model has a wrong surface pressure-wind relationship. Given a strong wind speed (say 120 knots), temperature anomaly at hurricane core region in the model is much warmer than observation. If we use the observation data (without modification), we will destroy the model-consistency of the vortex (or significantly reduce the maximum wind speed if model-consistency maintains).

### 2) Radar data from observation

Let's only consider the eyewall size here. 2005 Wilma has a 9-km eyewall size at 140 knots. The model can't produce 9-km eyewall size. In fact, if we have 3D wind data and produce a nice initial vortex with 9-km eyewall, the eyewall will collapse, and significant spin-down will occur in model forecast. In the min-analysis, we only reduce 15% of the model value and always keeps the eyewall size larger than 19-km.