Vortex Initialization in HWRF Model

HWRF Tutorial, 2016

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Outline

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3.Bogus storm

4. Storm relocation

5. Storm size correction

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1. Overview

- **HWRF initialization design:**

  Mini analysis for background vortex + GSI (Hybrid)

  - **The mini analysis is to create a better background fields, and includes three parts:**
    - ➔ **storm relocation** (data: storm center position)
    - ➔ **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)
    - ➔ **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

The following is considered:

1). No bogus data in data assimilation

Reasons: a) bogus data may conflict with observation data

b) we will get the storm structure we specified

2) No conflict between the mini-vortex analysis and the traditional data assimilation

a) if we have no inner core data, and choose not to run GSI, the final analysis are (for West Pac and East Pac)

mini-vortex analysis + environmental field from GFS analysis

for hurricane model initialization

b) If we have inner core data (such as the airborne radar data), we can use the results from

mini-vortex analysis + GSI

to further improve the vortex structure and the environment fields through GSI data assimilation

3) Model-consistent

Generally speaking, the differences are large between the model and the observation in hurricane area. 1) We want the final analysis close to observation, 2) we also want the final analysis to be model consistent. We have two choices:

a) Small correction

pro: model-consistent

small adjustment in model first-guess

con: vortex structure may be bad

➔ HWRF initialization can be considered as small correction (correction is large in a few cases):

Storm size correction is limited to 15%

wind speed correction < 15% (in most of the cases)

3) Model-consistent (continue)

b) Large correction

pro: good vortex structure

con: generally speaking, Not model-consistent

Large adjustment in model first-guess

Once model forecast starts, the good vortex structure can be lost in several hours forecast time.

Case study: 2005 Wilma has an 8-km eyewall size at 140 knots wind. Model forecast gives ~ 20km eyewall size in the background fields. If we produce a nice initial vortex with 8-km eyewall size in HWRF initial fields, the eyewall will collapse, and significant spin-down will occur in model forecast. The current HWRF model does not have the capability to maintain this kind of hurricane structure.

2. HWRF Cycling System

- In HWRF analysis system, only the HWRF vortex is cycled, and the environment field comes from GDAS forecast or GFS, depending on the configuration/basin.

HWRF guess field = GDAS environment field

+ corrected vortex from HWRF 6h forecast

After the guess field is created, HWRF analysis will be performed to create HWRF analysis field.

- For East Pac and West Pac regions, the initialization is slightly different,

  Final analysis = environment field from GFS analysis

  + corrected 6h HWRF vortex

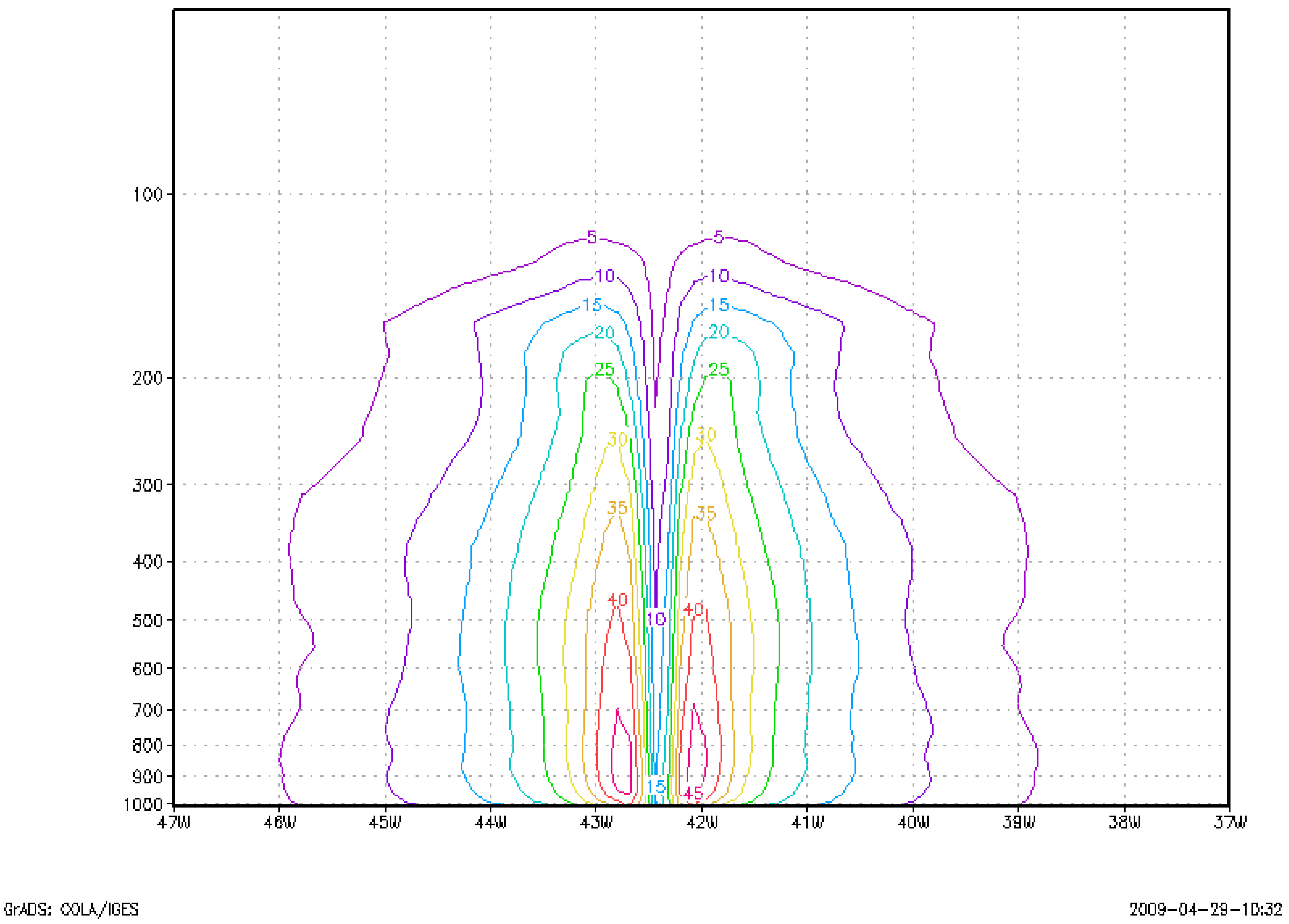
3. **Bogus vortex**

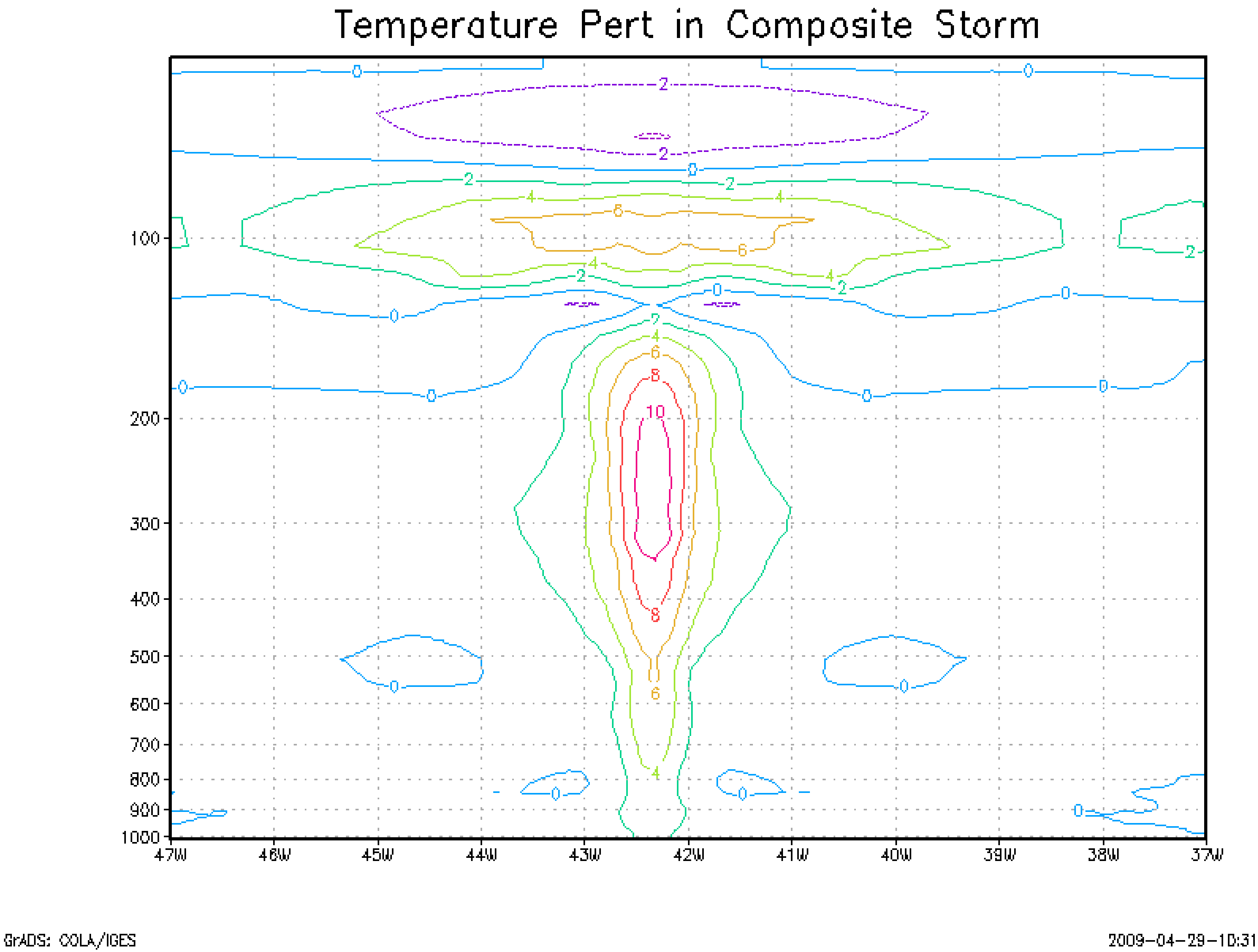
- Only used to increase storm intensity if background vortex is weaker compared to observation
- Cold start: background vortex comes from GDAS (or GFS) analysis
- Bogus storm has the same storm size as the observation
- Bogus storm is created from a 2D axi-symmetric composite vortex. The 2D axi-symmetric composite vortex is pre-generated.
- The 2D vortex has hurricane perturbations U, V, T, r (water vapor mixing ratio) and Ps

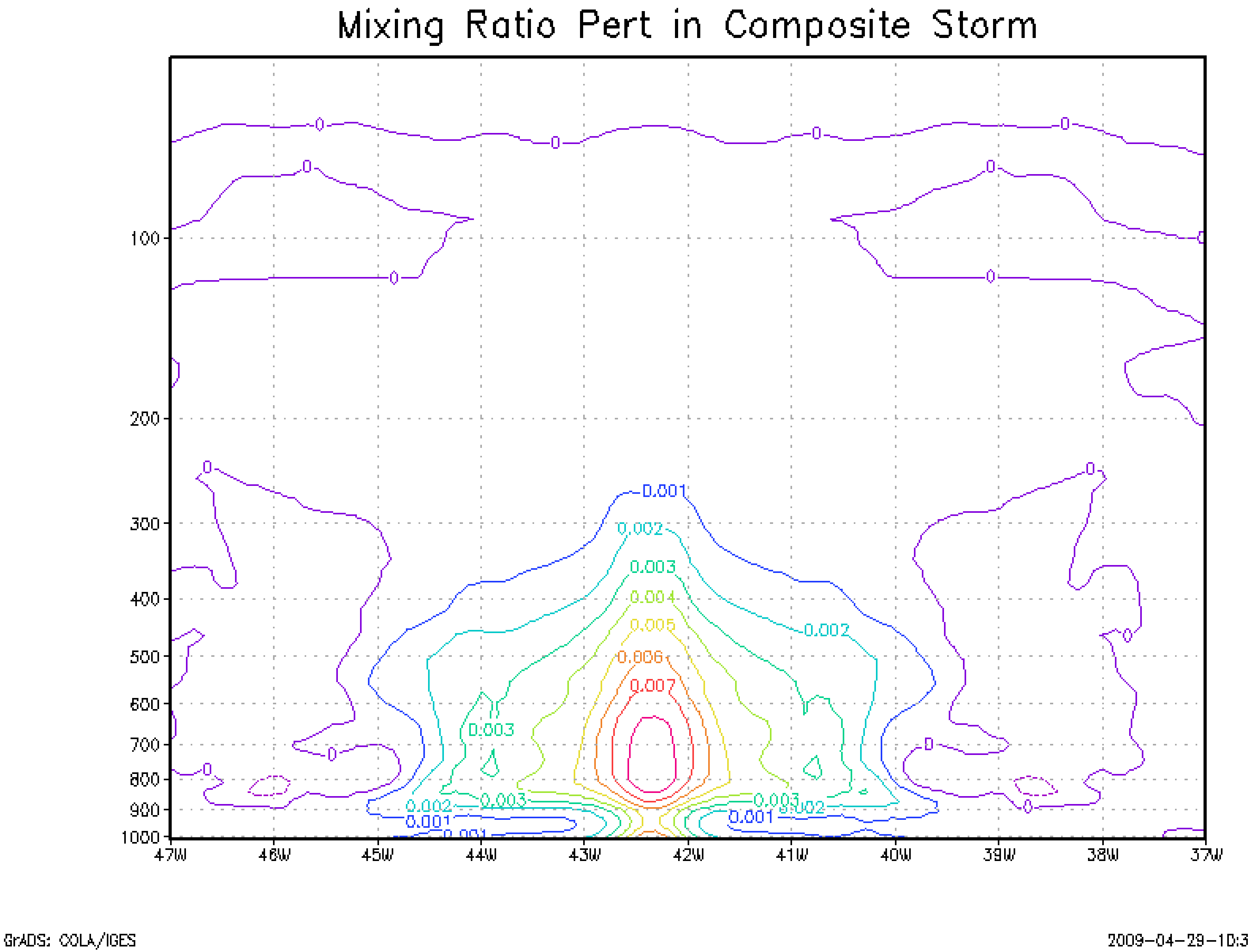
Bogus vortex (continue)

- 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.
  - After smooth, the storm size is corrected to match the observation
  - The 2D composite vortex should be recreated whenever the changes of model physics strongly affect the storm structures

Total Wind Speed (m/s) in Composite Storm




Temperature Pert in Composite Storm
100
200
300
400
500
600
700
800
900
1000
47W
46W
45W
44W
43W
42W
41W
40W
39W
38W
37W
GrADS: COLA/IGES
2009-04-29-10:31


Mixing Ratio Pert in Composite Storm
100
200
300
400
500
600
700
800
900
1000
47W
46W
45W
44W
43W
42W
41W
40W
39W
38W
37W
0.001
0.002
0.003
0.004
0.005
0.006
0.007
GrADS: COLA/IGES
2009-04-29-10:31

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 NHC'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. **<u>Storm Size</u> 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

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

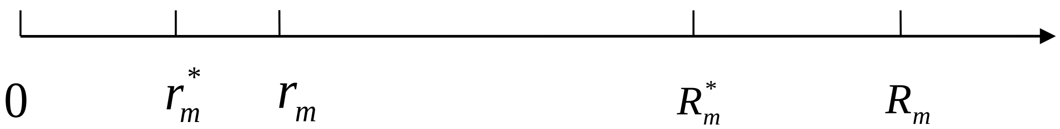
Integrate equation (4.1.1), we have

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

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

At $r = r_m$, $r^* = f(r_m) = r_m^*$ (1.4.1.3)

At $r = R_m$, $r^* = f(R_m) = R_m^*$ (1.4.1.4)

Storm Size Correction (continue)

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

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

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

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

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

Storm Size Correction (continue)

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

  As discussed in 2013 HWRF v3.5a Scientific Document, the minimum surface pressure needs to be scaled to observation value before calculating the radius of outermost closed isobar,

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

  Similar to the calculation of the radius of the outermost closed isobar, we need to scale the max wind speed for vortex #1 (background vortex) and vortex #2 (bogus vortex) before calculating the radius of 34 knot wind.

Storm Size Correction (continue)

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

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

$$\alpha_i = a = r_m^* / r_m = R_m^* / R_m \qquad (1.4.1.9)$$

  Since 2011 HWRF, the second parameter is added in the storm size correction according to equation (1.4.1.7)

Storm Size Correction (continue)

- Sea-level pressure adjustment

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

where,

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

And

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

Storm Size Correction (continue)

- Temperature adjustment

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

$$T^* = T_e + \Gamma \Delta T = T + (\Gamma - 1)\Delta T \qquad (1.4.1.2.9)$$

Storm Size Correction (continue)

- Water vapor adjustment

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

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

and

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

Storm Size Correction (continue)

- Convergence

  If α=1.0, no storm size correction, we have

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

from equations (1.4.1.1.9), (1.4.1.2.9) 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

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

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

    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 β, 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 β.

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

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

(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 observed 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,

      β is close to 1

      And the pressure adjustment is

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

and

$$\psi = \int_{\infty}^{r} \left(\frac{v_1^2}{r f_0} + v_1\right) dr \quad (1.4.2.2.2)$$

$$\psi^{new} = \int_{\infty}^{r} \left[\frac{(\beta v_1)^2}{r f_0} + \beta v_1\right] dr \quad (1.4.2.2.3)$$

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,

      β is close to 0
    - model consistent pressure adjustment

$$\Delta p^{new} = \Delta p \frac{\psi^{new}}{\psi} \qquad (1.4.2.2.7)$$

And

$$\psi_1 = \int_\infty^r \left(\frac{v_1^2}{rf_0} + v_1\right) dr \qquad (1.4.2.2.5)$$

$$\psi^{new} = \int_\infty^r \left[\frac{(v_1 + \beta v_2)^2}{rf_0} + (v_1 + \beta v_2)\right] dr \qquad (1.4.2.2.6)$$

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,

      β is close to 1

    Define $$\Gamma = \frac{\psi^{new}}{\psi}$$

    Then temperature fields can be corrected using equation (1.4.1.2.9), 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, β is close to 0

      Define $$\Gamma = \frac{\psi^{new}}{\psi}$$

      Then temperature field and moisture fields can be similarly corrected as in Case I.

Note: Intensity correction can be moderately large, the nonlinear effect of the balance equation is included in the formulation.

Storm Intensity Correction (continue)

- Convergence for intensity adjustment

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

In this case β=1.0, no wind speed correction, from equations (1.4.1.2.2), (1.4.2.2.3) and (1.4.1.2.5), we have, $\Gamma(r) = 1.0$

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

In Case II, β=0, no wind speed correction, from equations (1.4.2.2.5), (1.4.1.2.6), we have (1.4.1.2.7), $\Gamma(r) = 1.0$

From equations (1.4.1.1.9), (1.4.1.2.9) and (1.4.1.3.6), there will be no adjustments in 2D surface pressure, 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)

- **Limitation in current operational HWRF vortex initialization**

  The purpose of the mini-analysis is to create better background fields using TCVitals. Then add 3D data on top of the new vortex. The current GSI has the capability to add airborne radar data. Since the airborne radar data are expensive to collect, only less than 10% of the forecast cycles have these data. So, for most of the storms, we only have the low level control, upper level structure (for example, storm depth) may be very different from observation, particularly in shear environment.

- **Current work in HWRF vortex initialization**

  We are working to add the satellite radiance data in the hurricane core area. We have made very good progresses. We are hoping a major improvement in hurricane intensity forecast after the work is completed.

Thank you very much for attending this tutorial !!!