Vortex Initialization in HWRF/HMON Models

HWRF Tutorial

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Outline

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3. Bogus storm
4. Storm relocation
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1. Overview

- **HWRF Initial Fields:**

  Vortex Initialization + GSI data assimilation

  - **The vortex initialization is to create a better background field using TcVital information,** 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 in vortex initialization:**

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

- **Creating HWRF initial fields:**

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 vortex initialization and data assimilation

a) if we have no data assimilation, we can use the results from

vortex initialization + environmental field from GFS analysis

for hurricane model initialization (currently used in HMON)

b) If we have data assimilation, we can add inner core data (such as the airborne radar data) through data assimilation,

vortex initialization + data assimilation

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. We have two choices:

a) Small correction

pro: model-consistent

small adjustment during model forecast

con: vortex structure may be bad

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

Storm size correction is limited to 15%

wind speed correction < 15% (generally speaking)

As model physics improve, the vortex structure will become better, and the final analysis eventually will converge to observation.

Model-consistent (continue)

b) Large correction

pro: better vortex structure

con: most likely not model-consistent

Large adjustment during model forecast

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

Example: 2005 Wilma has an 8-km eyewall size at 140 knots wind. Model forecast gives ~ 20km eyewall size in the background fields. If we force the initial vortex to be 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 guess field comes from GDAS forecast (global model).

  HDAS guess field = GDAS environment field

  + corrected vortex from HWRF 6h forecast

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

- If there are no data assimilation, the initial field will be,

  Final analysis = environment field from GFS analysis

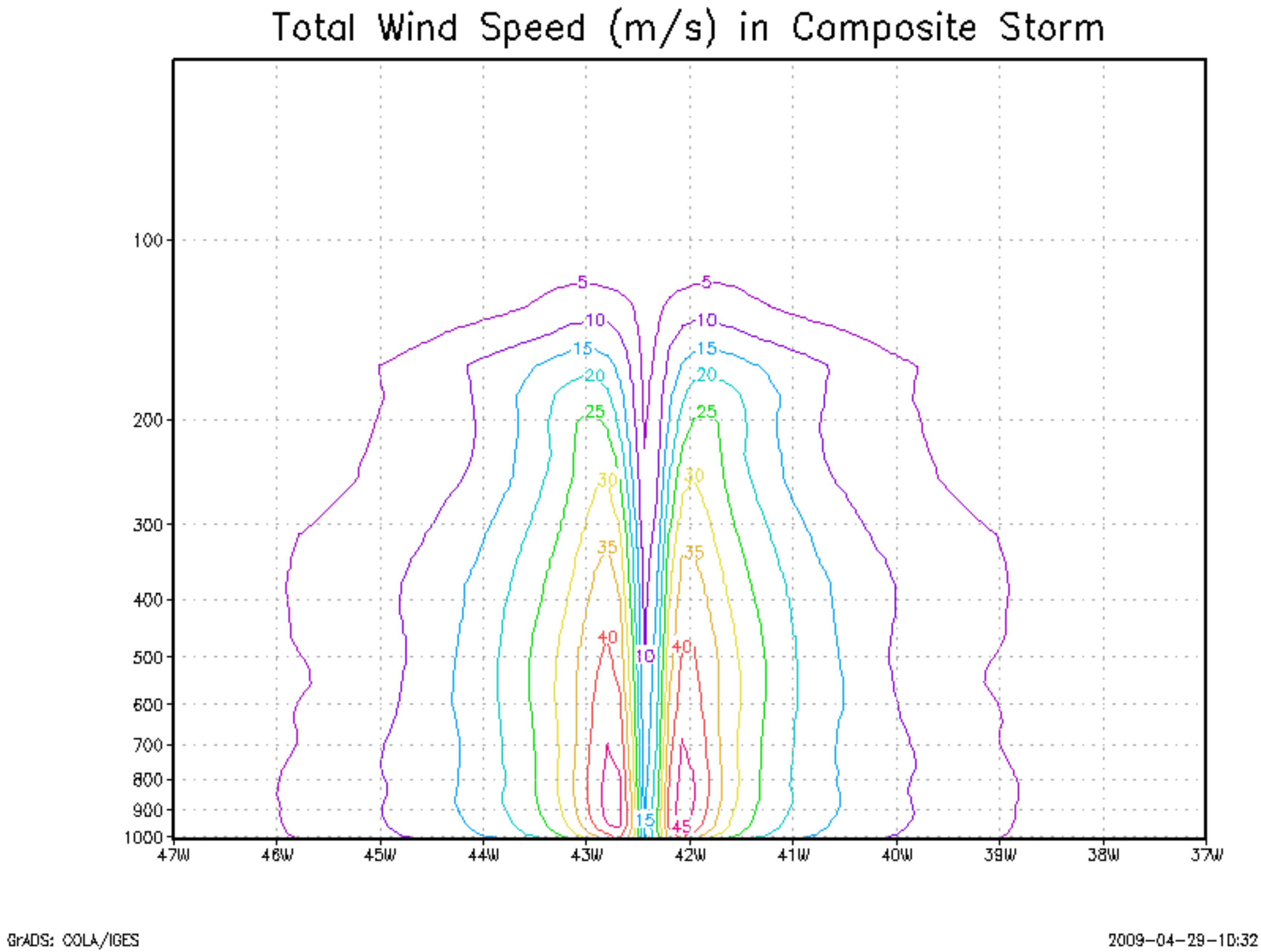
  + corrected 6h HWRF vortex

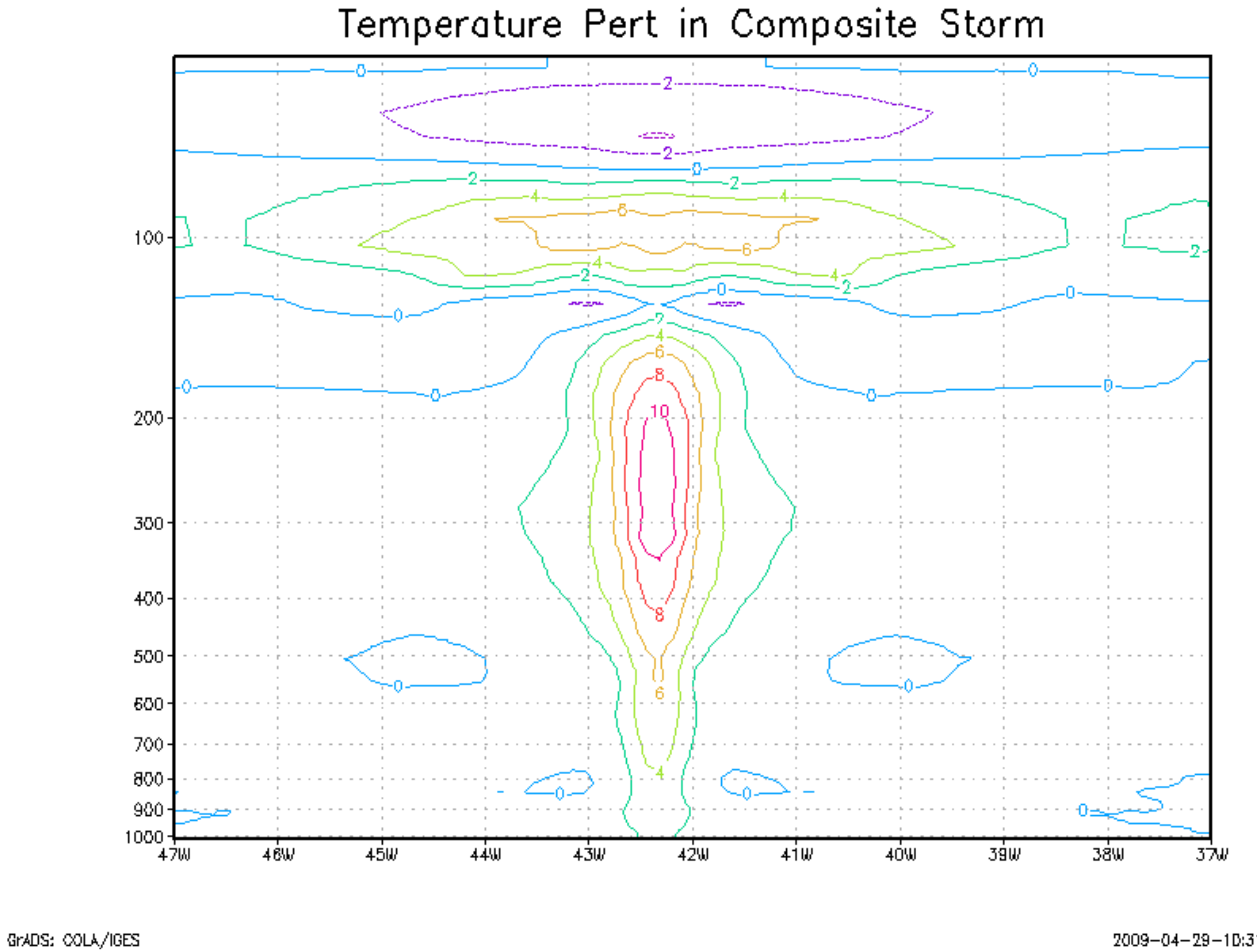
3. **Bogus vortex**

- Cold start:
  - If vobs < 20 m/s, background vortex comes from GFS analysis
  - if vobs > 20 m/s, background vortex will be bogused
- Warm start:
  - Bogus storm only be used to increase storm intensity if background vortex is weaker compared to observation
- 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

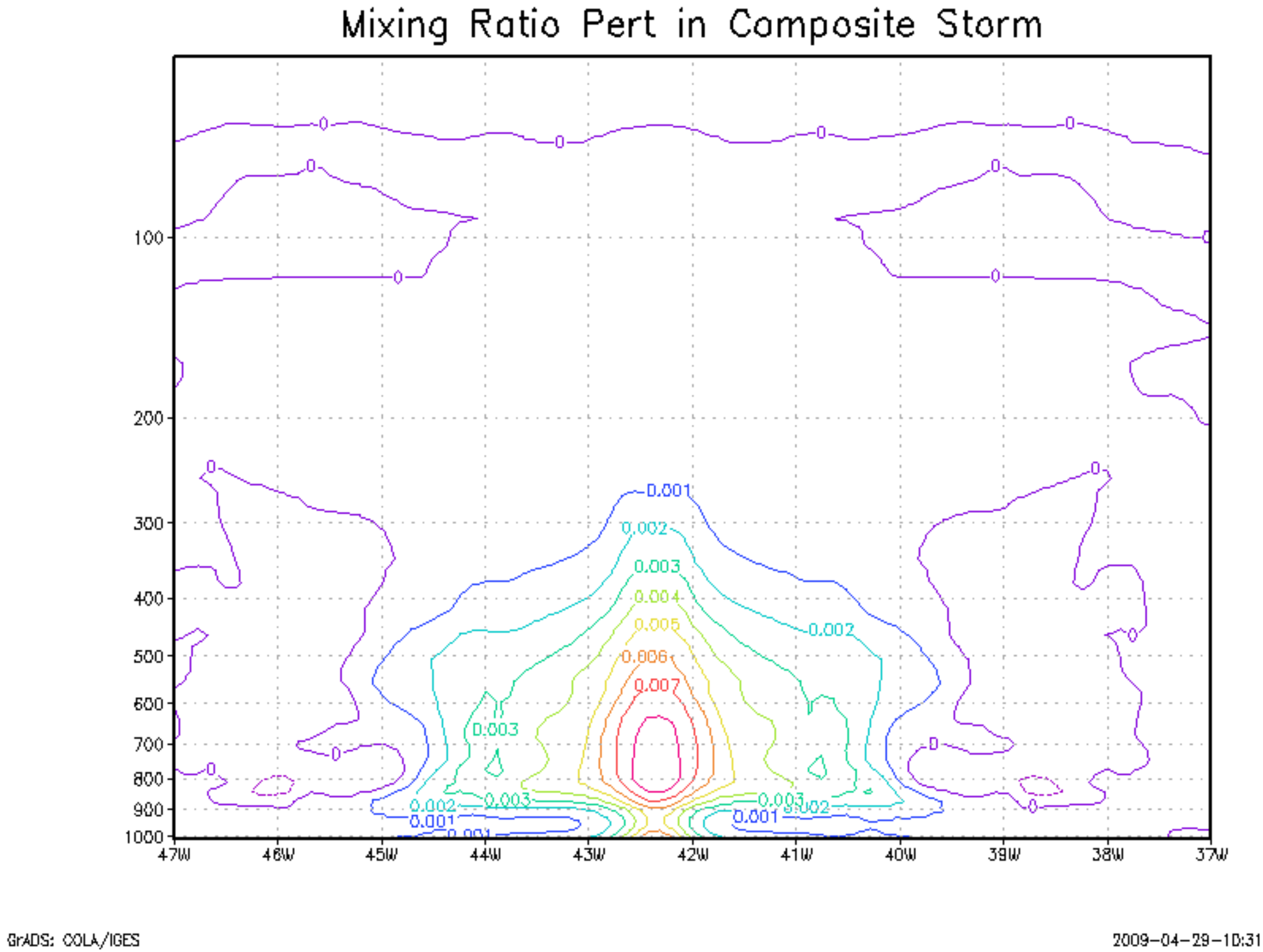
Bogus vortex (continue)

- 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
  - Interpolate the 2D vortex onto 3D model grid
- 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
100
200
300
400
500
600
700
800
900
1000
47W
46W
45W
44W
43W
42W
41W
40W
39W
38W
37W
5
10
15
20
25
30
35
40
45
GrADS: COLA/IGES
2009-04-29-10:32



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
0.001
0.002
0.003
0.004
0.005
0.006
0.007
GrADS: COLA/IGES
2009-04-29-10:31

4. Storm relocation

Storm relocation 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*

Storm relocation is done in HWRF in a slightly different way

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

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

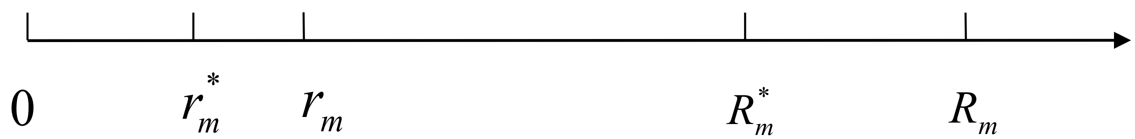
Integrate equation (4.1.1), we have

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

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),

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

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

- 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 outmost closed isobar from model output**

  As discussed in HWRF Scientific Document, the minimum surface pressure need to be scaled to observation value (for vortex #1 and vortex #2) before calculating the radius of outmost closed isobar

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

  Similar to the calculation of the radius of the outmost closed isobar, we need to scale the max wind speed to observation value for vortex #1 and vortex #2 before calculating the radius of 34 knot wind.

  vortex #1: vortex from HWRF 6h forecast (or GFS analysis)

  vortex #2: bogus vortex (axi-symmetric vortex)

- Sea-level pressure adjustment

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

where,

$$\psi^{*} = \int_{\infty}^{r^{*}} \left(\frac{v^{2}}{r^{*} f_{0}} + v\right) dr^{*} \qquad (1.4.1.1.6)$$

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,

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

- 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

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

- 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.

- 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

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

and

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

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

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), which are the same as those in storm size corrections.

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**

- **Vortex initialization can be considered as a mini data analysis for storm vortex using TcVital information, and 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 storm location, storm size and storm intensity in the background fields match the observations, there will be no changes to any of the background fields

Summary and discussions (continue)

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

  The purpose of the vortex initialization 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 compared to observation, particularly in shear environment.

- **Continue improvement in HWRF intensity forecast**

  It is possible to add the satellite radiance data in the inner core area to correct the hurricane structure through vortex initialization. However, adding satellite radiance data through data assimilation might be a better way. We are hoping the hurricane intensity forecast will continue to improve as more and more inner core data are used in data assimilation.

  If there is no data assimilation in hurricane model, inner core data should be added through vortex initialization even though it is a challenging task.

Thank you very much

for attending this tutorial !!!