Vortex Initialization in HWRF Models
Outline

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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.
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
Temperature Pert in Composite Storm
4. Storm relocation

Storm relocation to initialize hurricanes was implemented in GFS T1534. 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 IMD'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**

\[ \alpha_i = \frac{\Delta r^*_i}{\Delta r_i} = a + br_i \]  \hspace{1cm} (1.4.1.1)

Integrate equation (4.1.1), we have

\[ r^* = f(r) = ar + \frac{1}{2}br^2 \]  \hspace{1cm} (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 \((r_m \text{ and } r_m^*)\)
  – Radius of the outmost closed isobar \((R_m \text{ and } R_m^*)\)
    • Model data: \(r_m, R_m\)
    • Observation data: \(r_m^*, R_m^*\)

\[
\begin{align*}
0 & \quad r_m^* & \quad r_m & \quad R_m^* & \quad R_m \\
\end{align*}
\]

• We compress/stretch the model grids such that
  
  \[
  \text{At } r = r_m, \quad r^* = f(r_m) = r_m^* \quad (1.4.1.3)
  \]
  \[
  \text{At } r = R_m, \quad r^* = f(R_m) = R_m^* \quad (1.4.1.4)
  \]
• Substituting (1.4.1.3) and (1.4.1.4) into (1.4.1.2),

\[
ar_m + \frac{1}{2} b r_m^2 = r_m^* \quad (1.4.1.5)
\]

\[
a R_m + \frac{1}{2} b R_m^2 = R_m^* \quad (1.4.1.6)
\]

• 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 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)
Storm Size Correction (continue)

- **Sea-level pressure adjustment**

\[ \Delta p^* = \Delta p \frac{\psi^*}{\psi} = \Delta p \cdot \Gamma \]  \hspace{1cm} (1.4.1.1.9)

where,

\[ \psi^* = \int_0^{r^*} \left( \frac{v^2}{r^* f_0} + v \right) dr^* \]  \hspace{1cm} (1.4.1.1.6)

And

\[ \psi = \int_0^{r^*} \frac{1}{\alpha(r^*)} \left[ \frac{v^2}{r^*} \frac{f(r^*)}{r^* f_0} + v(r^*) \right] dr^* \]  \hspace{1cm} (1.4.1.1.4)
• **Temperature adjustment**

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

\[
T^* = T_e + \Gamma \Delta T = T + (\Gamma - 1) \Delta T \tag{1.4.1.2.9}
\]
Storm Size Correction (continue)

• Water vapor adjustment

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

\[ q^* \approx \frac{e^*}{e} q \approx \frac{e_s^*}{e_s} q \approx q + \left( \frac{e_s^*}{e_s} - 1 \right) q \]  \hspace{1cm} (1.4.1.3.4)

and

\[ \frac{e_s^*}{e_s} = \exp\left[ \frac{17.67 \times 243.5(T^* - T)}{(T^* - 29.66)(T - 29.66)} \right] \] \hspace{1cm} (1.4.1.3.6)
Storm Size Correction (continue)

• Convergence

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

$$\Gamma(r^*) = \frac{\psi^*}{\psi} = 1.0$$

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
    \[
    F_1 = \sqrt{(u_1 + u_2)^2 + (v_1 + v_2)^2} \]  
    \[
    F_2 = \sqrt{(u_1 + \beta u_2)^2 + (v_1 + \beta v_2)^2} \]  
    (1.4.2.1.1)  
    (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**

\[
\begin{align*}
    u(x, y, z) &= u_1(x, y, z) + \beta u_2(x, y, z) \\
    v(x, y, z) &= v_1(x, y, z) + \beta v_2(x, y, z)
\end{align*}
\]

And

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

(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, \( \beta \) is close to 1

And the pressure adjustment is

\[
\Delta p^{\text{new}} = \Delta p \frac{\psi^{\text{new}}}{\psi}
\]  

(1.4.2.2.5)

and

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

(1.4.2.2.2)

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

(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
    • model consistent pressure adjustment

\[
\Delta p^{new} = \Delta p \frac{\psi^{new}}{\psi} \quad (1.4.2.2.7)
\]

And

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

\[
\psi^{new} = \int_{\infty}^{r} \left[ \frac{(v_1 + \beta v_2)^2}{rf_0} + (v_1 + \beta v_2) \right] dr \quad (1.4.2.2.6)
\]
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,
    \( \beta \) 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, \( \beta \) is close to 0

\[
\Gamma = \frac{\psi^{\text{new}}}{\psi}
\]

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 $\beta=1.0$, 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, $\beta=0$, 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
HWRF Initialization - Analysis Time

7. HWRF Initialization Procedure

exhwrf_init.py for GDAS_FGAT=6

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exhwrf_init.py for GFS_FHR=0

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Color coding for file formats:
- FORTRAN Binary
- GRIB
- NetCDF

Vortex adjustment
HWRF Initialization with FGAT

HWRF Initialization - 3 h Prior

exhwrf_init.py for GDAS FGAT=3

Diagram of file flows and processes involved in HWRF initialization with FGAT.
HWRF Initialization with FGAT

HWRF Initialization - 3 h After Analysis

exhwrfinit.py for GDAS FGAT= 9
The vortex correction adjusts the location, size, and structure based on the TCVitals:

- storm location (data used: storm center position);
- storm size (data used: radius of maximum surface wind speed. 34-kt wind radii, and radius of the outmost closed isobar); and
- storm intensity (data used: maximum surface wind speed and, secondarily, the minimum sea level pressure).
HWRF-Vortex Initialization (stages I and II)

Stage I - Runs if previous HWRF available and obs intensity >=14 m/s

1. Interpolate 6-h forecast vortex from previous HWRF cycle to 3X domain
2. Process track of previous HWRF forecast to find vortex position
3. Separate 3X data onto environment and storm
4. Adjust HWRF vortex

Stage II - Always runs

1. Rebalance inner nest domain data
2. Interpolate data from d01, d02 and d03 onto 3X domain
3. Process track of previous GFS forecast to find vortex position
4. Separate 3X data onto environment and storm

Stage I is used to split the previous HWRF forecast onto storm and environment so that the vortex can be adjusted and relocated. This is not done when the storm is very weak as it is best to use the GFS vortex in that case.

Stage II is used to split the global forecast to get the environment.
HWRF-Vortex Initialization (stage III)

Cold and observed intensity < 20 m/s
Cycled and observed intensity < 14 m/s

Adjust the global vortex and add it to the environment flow

If vortex+env flow is weaker than obs, further adjust the vortex

Interpolate to d01, d02, d03

Cycled and observed intensity >= 14 m/s

Adjust HWRF vortex obtained in Stage 1 and add it to the environment flow

If vortex+env flow is weaker than obs, further adjust the vortex

Interpolate to d01, d02, d03

Cold and observed intensity >= 20 m/s

Prepare bogus vortex

Interpolate to d01, d02, d03

Stage III
- For cold starts, bogus strong storms but use global vortex for weak ones.
- For cycled starts, use HWRF vortex for strong storms but cycle global vortex for weak ones.
Conventional observations (contained in prepbufr file) assimilated in ghost d02 and ghost d03 domains include:
- radiosondes;
- dropwindsondes;
- aircraft reports (AIREP, RECCO, MDCRS-ACARS, TAMDAR, AMDAR);
- surface ship and buoy observations;
- surface observations over land;
- pibal winds;
- wind profilers;
- radar-derived Velocity Azimuth Display (VAD) wind;
- WindSat scatterometer winds; and
- integrated precipitable water derived from the Global Positioning System.

Satellite observations assimilated in ghost d02 domain include:
- Radiances from IR instruments: HIRS, AIRS, IASI, GOES Sounders
- Radiances from MW instruments: AMSU-A, MHS, ATMS
- Satellite derived wind: IR/VIS cloud drift winds, water vapor winds
8. **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