Improving High-Resolution Tropical Cyclone Prediction Using a Unified GSI-based Hybrid Ensemble-Variational Data Assimilation System for HWRF

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with
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HFIP first year review, July 10, 2013
The GSI-based hybrid DA system showed significant improvement for global forecast compared to GSI 3DVAR and became operational on May 22, 2012 for Global Forecast System (GFS).

GSI is a unified system which provides data assimilation for all operational global and regional forecast system.
Background

- Efforts are being conducted to integrate the same GSI-based hybrid DA system with operational regional forecast systems.

- Unifying GSI-based hybrid DA system with operational regional systems facilitates faster transition to operations.

- The focus of the project is the extension, application, testing and research of the GSI-based hybrid data assimilation for the HWRF modeling system at high resolutions.

- Also motivated by encouraging results of ensemble based data assimilation for tropical cyclones.
Background

- Hurricane IKE 2008
- WRF ARW: $\Delta x=5\text{km}$
- Observations: radial velocity from two WSR88D radars (KHGX, KLCH)
- WRFVAR hybrid DA system (Wang et al. 2008ab, MWR)

Li et al., 2012, MWR
GSI-based Hybrid ensemble-VAR DA system

1-way coupling

member 1 forecast

EnKF

EnKF analysis 1

member 1 forecast

member 2 forecast

EnKF

EnKF analysis 2

member 2 forecast

member k forecast

Ensemble covariance

EnKF

EnKF analysis k

member k forecast

control forecast

GSI-ECV

data assimilation

control analysis

control forecast

First guess forecast

Wang, Parrish, Kleist, Whitaker 2013, MWR
GSI-based Hybrid ensemble-VAR DA system

2-way coupling

- member 1 forecast
- member 2 forecast
- member k forecast
- control forecast

EnKF
- EnKF analysis 1
- EnKF analysis 2
- EnKF analysis k

Ensemble covariance

GSI-ECV
- control analysis

Re-center EnKF analysis ensemble to control analysis
- member 1 analysis
- member 2 analysis
- member k analysis

First guess forecast

Wang, Parrish, Kleist, Whitaker 2013, MWR
GSI-based hybrid ensemble-variational DA system

- **GSI-ECV**: Extended control variable (ECV) method (Wang 2010, MWR):

\[
J(x', \alpha) = \beta_1 J_1 + \beta_2 J_e + J_o
= \beta_1 \frac{1}{2} x'_1^T B^{-1} x'_1 + \beta_2 \frac{1}{2} \alpha^T C^{-1} \alpha + \frac{1}{2} (y^{o'} - Hx')^T R^{-1} (y^{o'} - Hx')
\]

Extra term associated with extended control variable

\[
x' = x'_1 + \sum_{k=1}^{K} (\alpha_k \circ x_k^e)
\]

Extra increment associated with ensemble

- **EnKF**: square root filter interfaced with GSI observation operator (Whitaker et al. 2008, MWR)
System development and enhancement

- Develop interface to integrate both EnKF and GSI-ECV components with HWRF; different from H213 where ensemble is provided from GFS ensemble.

- Add/enhance inner core airborne radar data assimilation capability

- Enhance dual resolution assimilation capability

- Development/enhancement for GSI-ECV and airborne radar data have been transitioned into 2013 operational HWRF (H213)
Why Hybrid? “Best of both worlds”

Summarized in Wang 2010, MWR

<table>
<thead>
<tr>
<th>Benefit from use of flow dependent ensemble covariance instead of static B</th>
<th>Yes</th>
<th>Yes</th>
<th>Hamill and Snyder 2000; Lorenc 2003; Wang et al. 2007ab,2008ab, 2009; Buehner et al. 2010ab; Wang 2011, Zhang and Zhang 2012, etc.</th>
</tr>
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<tbody>
<tr>
<td>Robust for small ensemble or large model error</td>
<td>Yes</td>
<td></td>
<td>Wang et al. 2007b, 2009; Buehner et al. 2010b</td>
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<tr>
<td>Better localization for integrated measure, e.g. satellite radiance; radar with attenuation</td>
<td></td>
<td>Yes</td>
<td>Campbell et al. 2010</td>
</tr>
<tr>
<td>Flexible to add various dynamical/physical constraints</td>
<td>yes</td>
<td></td>
<td>Wang et al. 2013</td>
</tr>
<tr>
<td>Use of various existing capabilities in VAR (e.g., Outer loops to treat nonlinearity; Variational QC)</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Test with Hurricane Sandy, Oct. 2012

- Complicated evolution
- Tremendous size
- 147 direct deaths across Atlantic Basin
- US damage $50 billion

New York State before and after
nhc.noaa.gov
Experiment Design

- Model: HWRF
- Observations: radial velocity from Tail Doppler Radar (TDR) onboard NOAA P3 aircraft
- Initial and LBC ensemble: GFS global hybrid DA system
- Ensemble size: 40
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Evolution during TDR missions

1. Tropical to Non-Tropical
2. Non-Tropical back to Tropical
3. Tropical
4. Re-Intensify
5. Extra-Tropical
6. Landfall
DA cycling configuration (mission 1)

- **GSI (3DVAR, Static)**
  - Cold Start
  - Spin-up Forecast
  - OBS
  - DA Cycle
  - Deterministic Forecast

- **Hybrid (1 way coupling)**
  - Cold Start
  - Spin-up Forecast
  - OBS
  - Ensemble Perturbation
  - Deterministic Forecast

- **EnKF**
  - Cold Start
  - Ensemble Spin-up Forecast
  - DA Cycle
  - Deterministic Forecast
TDR data distribution (mission 1)

Vr & flight track 2200Z25

Vr & flight track 0030Z26

Vr & flight track 0200Z26

Vr & flight track 2330Z25
TDR data distribution (mission 1)

Vr vertical distribution

- Leg-4
- Leg-3
- Leg-2
- Leg-1

Height (hPa) vs Number of Obs.
Verification against SFMR wind speed

First Leg

Acknowledged HRD to make SFMR, flight level data available
Verification against SFMR wind speed

Last Leg

Graphs showing SFMR wind speed for different legs.
Comparison with HRD radar wind analysis
Comparison with radar wind analysis
Track forecast (RMSE for 7 missions)
Track forecast (error distribution)
MSLP forecast (error distribution)
Max wind forecast (error distribution)
Max wind and MSLP relationship
Test with IRENE 2011

- Model: HWRF
- Observations: radial velocity from Tail Doppler Radar (TDR)
- Initial and LBC ensemble: GFS global hybrid DA system
- Ensemble size: 40
Verification against independent flight level wind speed

First Leg

**Static**

**hybrid**
Verification against SFMR wind speed

First Leg

Static

hybrid
Verification against independent flight level wind speed

Last Leg

**static**

**hybrid**
Verification against SFMR wind speed

Last Leg

**static**

**hybrid**
Comparison with HRD radar wind analysis
Comparison with radar wind analysis

HRD radar wind analysis @ 1km

static @ 1km

Hybrid @ 1km
Comparison with radar wind analysis

HRD radar wind analysis @ 3km

static @ 3km

Hybrid @ 3km

m/s
3km-9km dual resolution hybrid DA with moving nest
3km-9km dual resolution hybrid DA with moving nest
Summary and ongoing work

a. The GSI-based hybrid EnKF-Var data assimilation system including both the Var and EnKF components were expanded to HWRF.
b. TDR data assimilation capability was added/enhanced for the HWRF hybrid DA.
c. Some of the development/enhancement is transitioned in 2013 HWRF operational DA system.
d. TDR data improved TC structure analysis and forecast, TC track and MSLP forecasts.
e. Various diagnostics and verifications suggested incorporating ensemble in GSI hybrid provided more skillful TC analysis and forecasts than the GSI 3DVar.
f. Testing more missions/cases.
g. Develop and research on various new capabilities for HWRF hybrid (dual resolution hybrid, etc.).
Comparison with radar wind analysis
700 mb wind increment

GSI 3DVar

3DEnsVar
Track forecast

EMC: HWRF official forecast
NoDA: no TDR assimilation
GSI: assimilating TDR using GSI 3DVar
EnKF: assimilating TDR using EnKF
Hybrid: assimilating TDR using hybrid
MSLP forecast

EMC: HWRF official forecast
NoDA: no TDR assimilation
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