Impacts of Assimilating Airborne Tail Doppler Radar Observations using the GSI-based Hybrid Ensemble-Variational Data Assimilation System for HWRF to Improve Operational High-Resolution Tropical Cyclone Prediction

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1. Introduction & Motivation

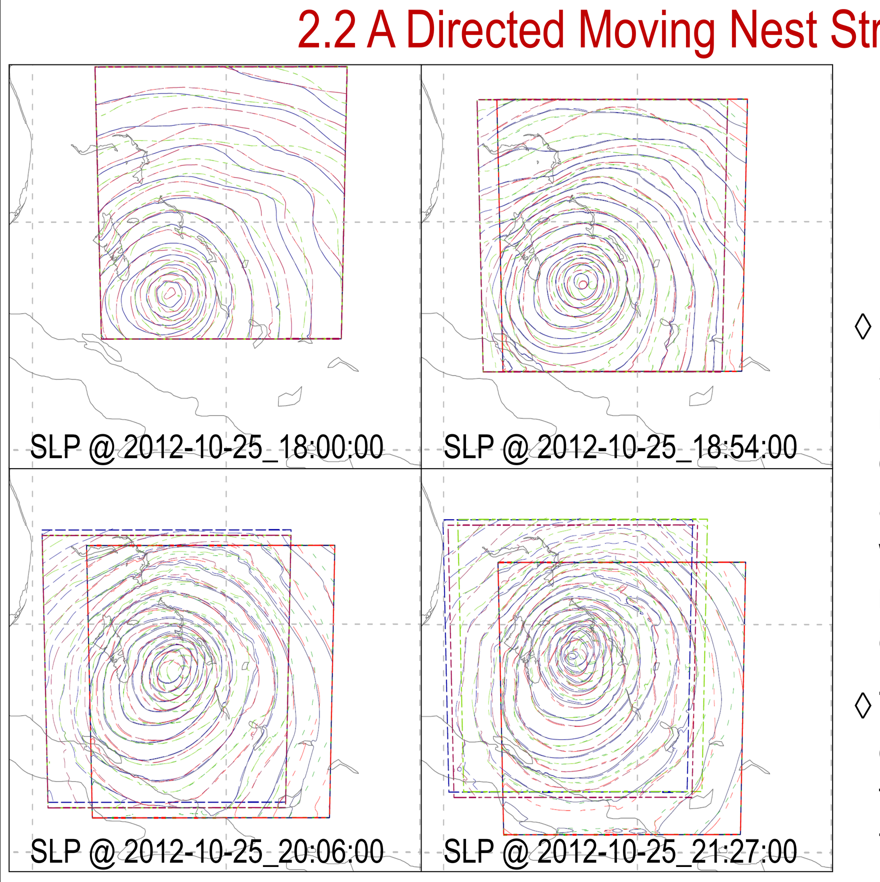
- In our previous study, a GSI-based hybrid ensemble-variational data assimilation system for HWRF was developed to assimilate the radial velocity data from Tail Doppler Radar (TDR) onboard NOAA P-3 aircrafts for hurricane initialization and prediction (Lu et al., 2015).
- Results showed that the hybrid system was able to correct both the wind and mass fields in a dynamically and thermodynamically coherent fashion. The impact of the TDR data was dependent on the data assimilation (DA) method; the hybrid system using self-consistent HWRF EnKF ensemble was found to improve both the analyzed TC structures and forecasts relative to GSI-3DVar and the hybrid ingesting GFS ensemble.
- Lu et al. 2015 only explored the hybrid DA system over a small period of the Tropical Cyclone (TC) lifetime which was covered by TDR data. Further exploration of the hybrid DA method for the entire life of TC assimilating both TDR and other observations is therefore needed. In addition, study of optimal configuration of the hybrid DA in the continuous DA cycling is still lacking.
- Therefore, we further develop the HWRF hybrid DA system based on Lu et al. 2015 to contain end-to-end continuous cycling capability to address the following questions: a) impact of dual resolution over single resolution; b) impact of different vortex initialization and relocation configurations; c) impact of 4DEnVar for vortex scale airborne radar observation; and d) how can the system help alleviate the spin-down issue.

2. Methodology and Experiment Design

2.1 Methodology

- GSI 3DEnVar (Wang 2010; Wang et al., 2014): $\mathbf{x}' = \mathbf{x}'_1 + \sum_{k=1}^{K} (\mathbf{a}_k \circ \mathbf{x}^e_k)$ $\quad J(\mathbf{x}'_1, \mathbf{a}) = \beta_1 \frac{1}{2}(\mathbf{x}'_1)^{\mathrm{T}} \mathbf{B}_1^{-1}(\mathbf{x}'_1) + \beta_2 \frac{1}{2}(\mathbf{a})^{\mathrm{T}} \mathbf{A}^{-1}(\mathbf{a}) + \frac{1}{2}(\mathbf{y}'^{o} - \mathbf{H}\mathbf{x}')^{\mathrm{T}} \mathbf{R}^{-1}(\mathbf{y}'^{o} - \mathbf{H}\mathbf{x}')$
- Dual Resolution Hybrid (Lei and Wang, 2015): $\mathbf{x}'_a = \mathbf{x}'_1 + D\sum_{k=1}^{K} \mathbf{a}_k \circ \mathbf{x}^e_k$ $\quad J(\mathbf{x}'_1, \mathbf{a}) = \beta_1 \frac{1}{2}(\mathbf{x}'_1)^T \mathbf{B}^{-1}(\mathbf{x}'_1) + \beta_2 \frac{1}{2}(\mathbf{a})^T \mathbf{A}^{-1}(\mathbf{a}) + \frac{1}{2}(\mathbf{y}^{o\prime} - \mathbf{H}\mathbf{x}'_a)^T \mathbf{R}^{-1}(\mathbf{y}^{o\prime} - \mathbf{H}\mathbf{x}'_a)$
- GSI 4DEnVar (Wang and Lei, 2014): $\mathbf{x}'_t = \sum_{k=1}^{K} [\mathbf{a}_k \circ (\mathbf{x}^e_k)_t]$ $\quad J(\mathbf{a}) = \frac{1}{2}\mathbf{a}^{\mathrm{T}} \mathbf{A}^{-1}\mathbf{a} + \frac{1}{2}\sum_{t=1}^{L} (\mathbf{y}^{o\prime}_t - \mathbf{H}_t \mathbf{x}'_t)^{\mathrm{T}} \mathbf{R}_t^{-1} (\mathbf{y}^{o\prime}_t - \mathbf{H}_t \mathbf{x}'_t)$
- Further details can be found in the references.

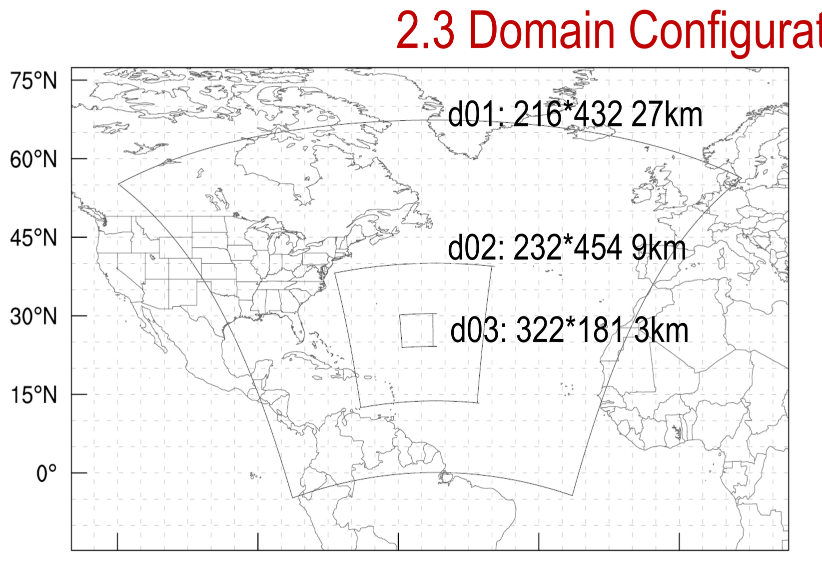
2.2 A Directed Moving Nest Strategy



◊ HWRF moving nest is storm following. A directed moving nest strategy is developed for HWRF to avoid difficulty associated with the divergence of moving nest locations in ensemble DA.

◊ The direction can be directed by model forecasts. Currently using tcvital.

2.3 Domain Configuration



Model: HWRF

Observations:

3km: conventional in-situ data in prepbufr, satellite wind, tcvital and TDR (whenever it is available)

9km: data types used by 3km + satellite radiances

Initial and LBC ensemble:

GFS global hybrid DA system

Ensemble size: 40

2.4 Experiment Descriptions

Experiment name	Description
Hybrid	6-hourly continuous end to end cycling
	3DEnVar hybrid with FGAT
	Dual-resolution hybrid (3km control ingests 9km ensemble);
	New directed moving nest strategy adopted; domains move for first 3 hour integration and stay for the next 6-hour integration.
	Control background: vortex relocation and initialization for the control background when no TDR; vortex relocation only when TDR.
	Ensemble backgrounds: vortex relocation
Hybrid-279	Same as "Hybrid" except it is not dual-resolution hybrid. Both hybrid control and ensemble are done at 9km resolution.
Hybrid-norelo	Same as "Hybrid" except it does not do any vortex initialization or relocation on control and ensemble backgrounds.
Hybrid-noensrelo	Same as "Hybrid" except it does not do relocation for ensemble backgrounds.
Hybrid-4DTDR	Same as "Hybrid" except it uses 4DEnVar in the TDR-involved cycles.
Hybrid-2015	Same as "Hybrid" except it uses a higher resolution (18/6/2 km) and physics consistent with the FY15 operational HWRF. It is running in near real time for 2015 hurricane season.

3. Results for Edouard (2014)

3.1 Impacts of dual resolution

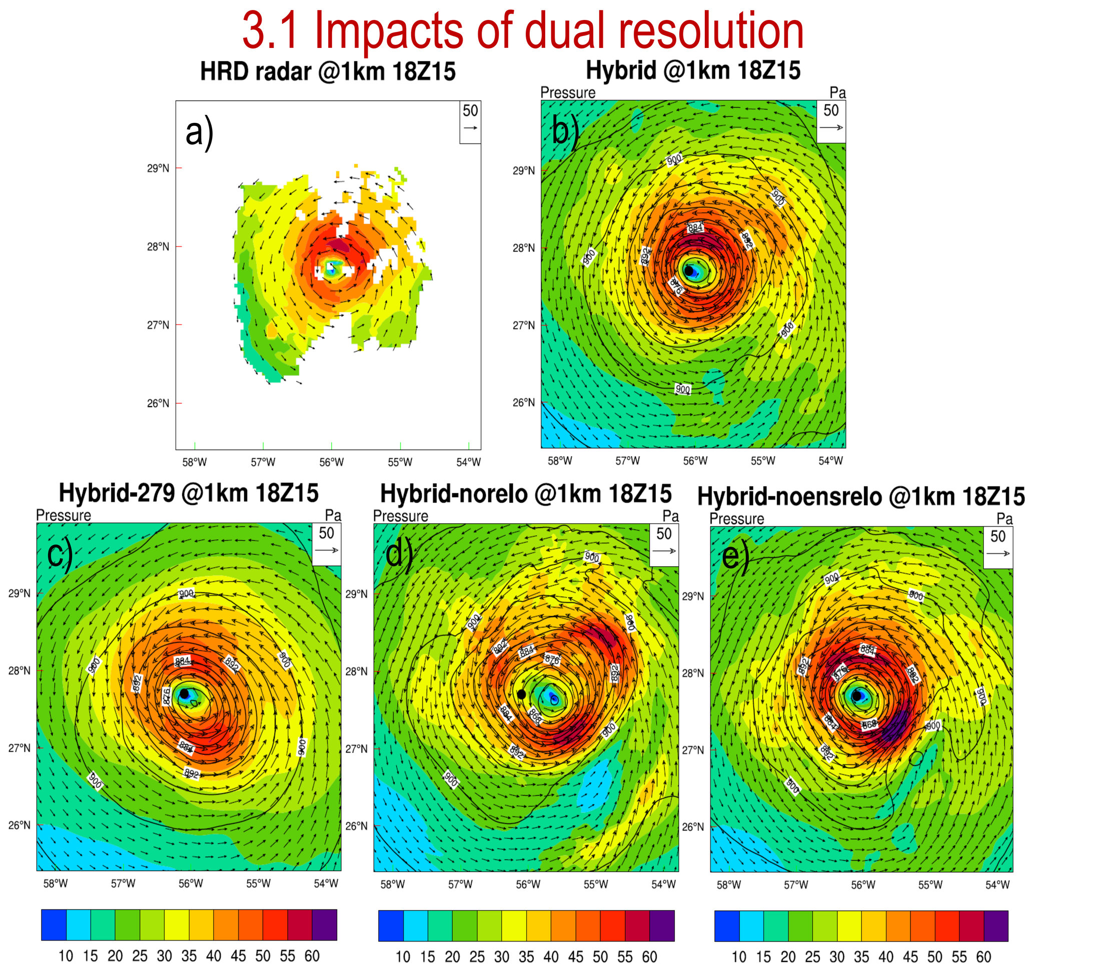


Fig. 3.1 Wind (shaded) and pressure (contour) analysis at 1 km height for a) HRD composite; b) Hybrid; c) Hybrid-279; d) Hybrid-norelo; and e) Hybrid-noensrelo for cycle No.17 @ 2014091518 UTC. Black dot denotes the observed center.

- Fig. 3.1 shows that the horizontal wind pattern generated by Hybrid (fig.3.1b) fit the HRD wind analysis (fig.3.1a) better than Hybrid-279 (fig. 3.1b).
- E.g., Hybrid captured the wind max in the north and the vortex is tighter than Hybrid-279.

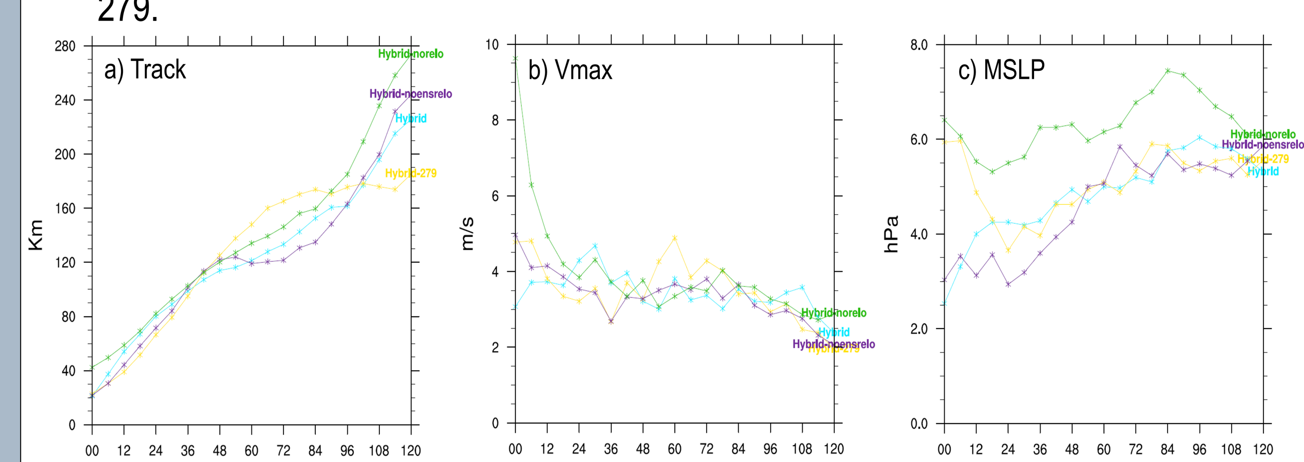


Fig. 3.2 Averaged forecast errors of a) Track, b) Vmax and c) MSLP of the 32 cycles from 201409111800 UTC to 201409191800 UTC during Edouard for Hybrid (light blue), Hybrid-279 (yellow), Hybrid-norelo (green) and Hybrid-noensrelo (purple)

- The Vmax (fig.3.2b) and MSLP (fig.3.2c) forecasts in Hybrid (light blue) were improved for the first 12~18 hours compared to those in Hybrid-279 (yellow).
- Together with the previous structure analyses in fig.3.1, Hybrid using dual resolution hybrid was better than Hybrid-279 which shows the positive impact of using a high resolution control analysis and forecast.

3.2 Impacts of vortex initialization and ensemble relocation

- ❖ Without any relocation or vortex initialization in both ensemble and control background, there was a large location error in Hybrid-norelo (fig.3.1d). The wind pattern generated by Hybrid-norelo was also less consistent with the HRD composite (fig.3.1a) compared to that generated by Hybrid (fig.3.1b). Together with the track (fig.3.2a), Vmax (fig.3.2b) and MSLP (fig.3.2c) forecasts in figure 3.2, Hybrid-norelo (green) showed the worst performance among all the experiments.
- ❖ If only doing relocation or vortex initialization for the control background, storm location in Hybrid-noensrelo (fig.3.1e) was more accurate than that in Hybrid-norelo (fig.3.1d). However, the wind field was spuriously strong and pressure field showed a spurious dipole feature. The forecasts in fig.3.2 also suggested that Hybrid-noensrelo (purple) was better than Hybrid-norelo (green), but it was still worse than Hybrid (light blue) especially for Vmax forecasts at early lead times due to the worse analysis.
- ❖ Therefore, Hybrid with both ensemble relocation and vortex relocation or initialization for the control was a better configuration than both Hybrid-noensrelo and Hybrid-norelo.

3.3 Impacts of 4DEnVar for vortex scale observation

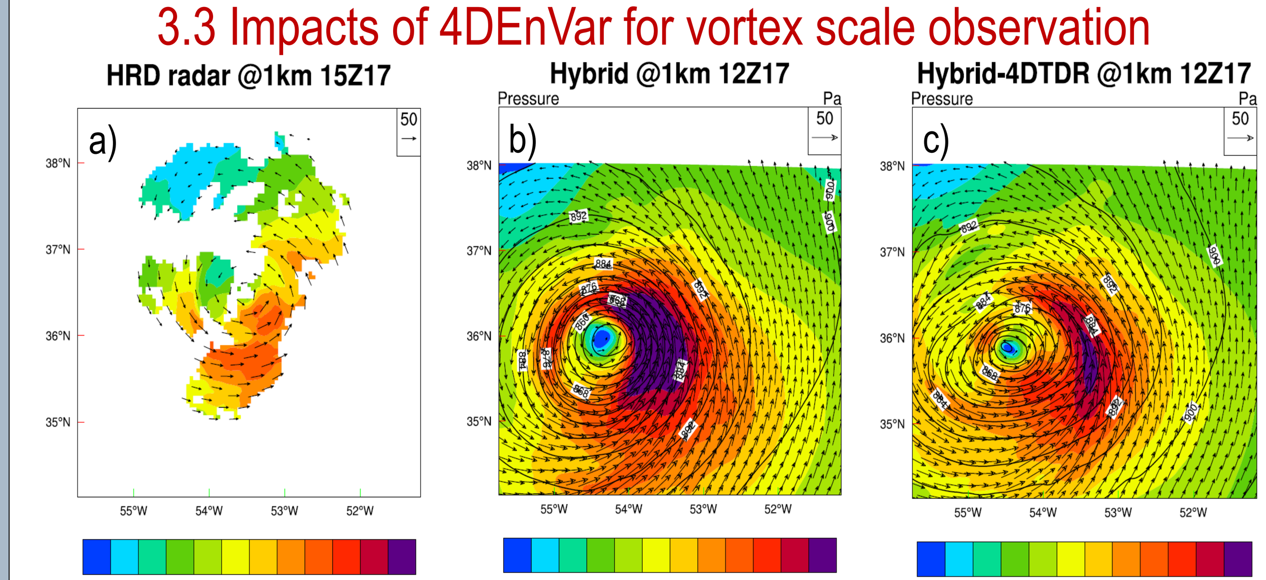


Fig. 3.3 Wind (shaded) and pressure (contour) analysis at 1 km height for a) HRD composite; b) Hybrid; and c) Hybrid-4DTDR for cycle No.24 @ 2014091712 UTC

- ♦ Spuriously large wind maximum analyses in Hybrid (e.g. fig.3.3b) with 3DEnVar were found in the last two TDR-involved cycles when the background forecast was going through rapid-changing eyewall replacement and the TDR data was brief and unevenly distributed over the 6-hour window (e.g. TDR covers 12:58~14:17 for cycle 24 valid at 12Z).
- ♦ Using 4DEnVar, the spurious wind maximum was reduced and the wind pattern was more consistent with HRD radar composite (fig.3.3a) in Hybrid-4DTDR (fig.3.3c).

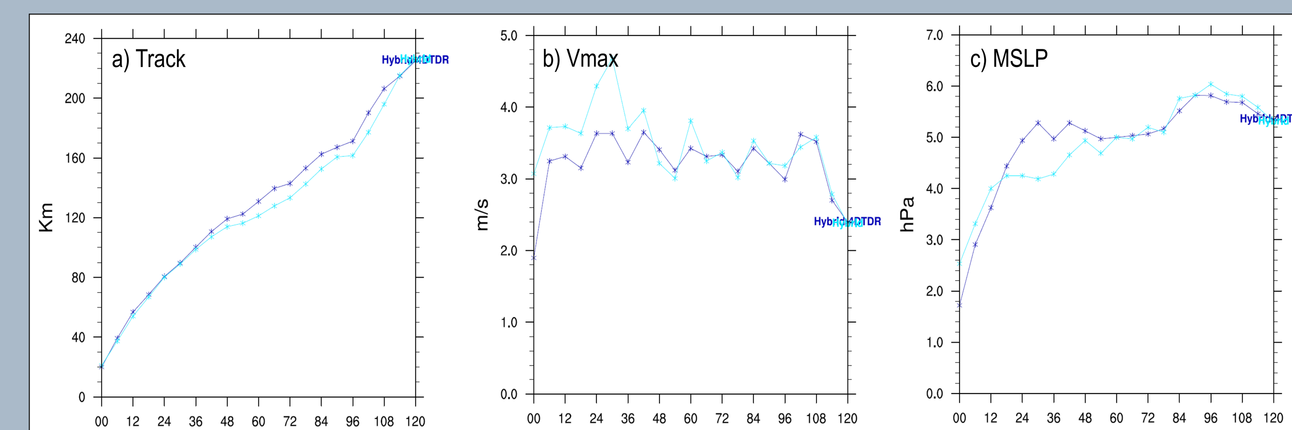


Fig. 3.4 Averaged forecast errors of a) Track, b) Vmax and c) MSLP of the 32 cycles from 201409111800 UTC to 201409191800 UTC during Edouard for Hybrid (dark blue) and Hybrid-4DTDR (light blue)

- ♦ Forecasts showed that the intensity forecasts (fig.3.4b & 3.4c) at early lead times were improved in Hybrid-4DTDR (dark blue) compared to those in Hybrid (light blue).
- ♦ Together with the previous structure analyses in fig.3.3, Hybrid-4DTDR, which used 4DEnVar in TDR-involved cycles, was better than Hybrid using purely 3DEnVar.

3.4 Alleviation of the "spin-down" issue

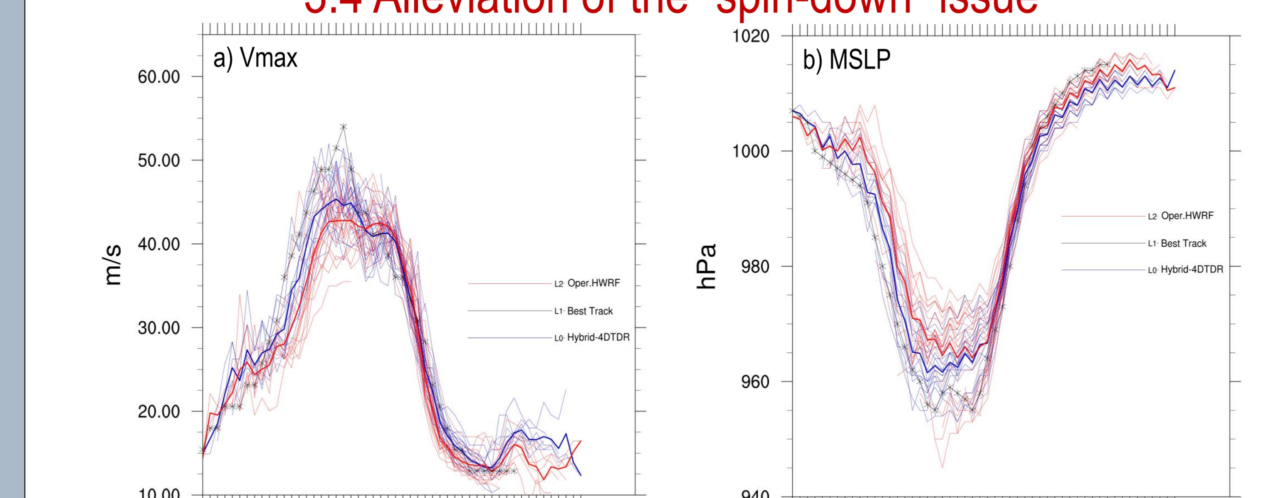


Fig.3.5 32 deterministic forecasts of a) Vmax and b) MSLP forecasts during Edouard from 201409111800 UTC to 201409191800 UTC for Best Track (black), Oper.HWRF (red) and Hybrid-4DTDR (dark blue). The averages for Oper.HWRF and Hybrid-4DTDR are marked in bolded line.

- ❑ Intensity forecasts (fig.3.5) in Hybrid-4DTDR (dark blue) showed improvements over those in the operational HWRF (red) during Edouard (2014).
- ❑ The improvements were found primarily during the intensification of Edouard until it reached the maximum intensity.

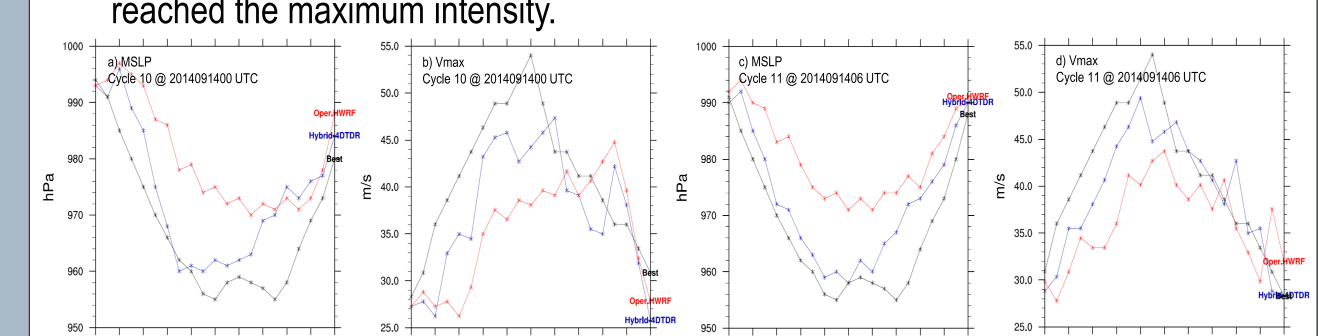


Fig.3.6 a), c) MSLP and b), d) Vmax forecasts for Hybrid-4DTDR (dark blue), Operational HWRF (red) and Best Track (black) for a), b) the 10th cycle valid at 2014091400 UTC and c), d) the 11th cycle valid at 2014091406 UTC

- ❑ The improvements in the intensity forecasts from Hybrid-4DTDR were due to the alleviation of the "spin down" issue presented in operational HWRF during the intensification of Edouard.

4. Ongoing and future work

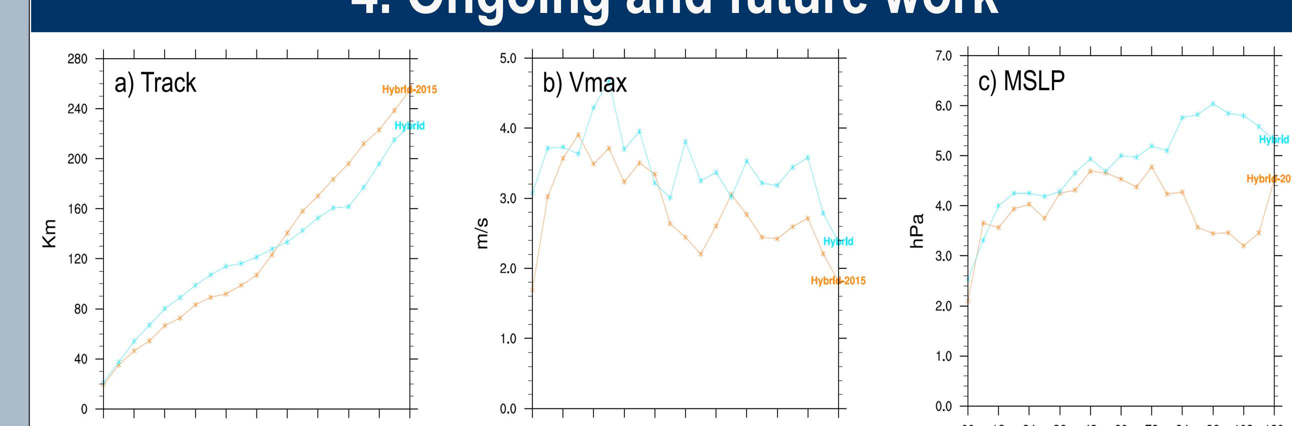


Fig.4.1 a) Track, b) Vmax and c) MSLP average forecast errors of the 32 cycles from 201409111800 UTC to 201409191800 UTC for Edouard for Hybrid (light blue) and Hybrid-2015 (gold)

- ✓ Using the physics and model resolution (18/6/2km) consistent with the FY15 operational HWRF, Hybrid-2015 (gold) improved over Hybrid (light blue) especially for the intensity forecasts.
- ✓ Hybrid-2015 configuration is running in near real time for the 2015 Hurricane season.

5. Summary

- ➢ Dual-resolution Hybrid provided better analysis of the inner core structure and better forecasts than single 9km resolution Hybrid-279.
- ➢ Hybrid-noensrelo with vortex relocation or initialization in control provided better analyses and forecasts compared to Hybrid-norelo. Hybrid with ensemble relocation can further improve the analyses and short-term forecasts over Hybrid-noensrelo.
- ➢ Hybrid-4DTDR further improved analyses and intensity forecasts over Hybrid for TDR DA.
- ➢ Hybrid-4DTDR showed improvements over operational HWRF in the intensity forecasts due to the alleviation of the "spin-down" issue during storm intensification.
- ➢ Efforts are being conducted to implement the end to end self-consistent hybrid DA system into the operational HWRF system. Further explorations to better utilize vortex scale data like TDR will be continued.

6. Acknowledgements and References

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