A GSI-based, End-to-End cycled, Dual Resolution Hybrid Ensemble-Variational Data Assimilation System for HWRF: system description and experiment results

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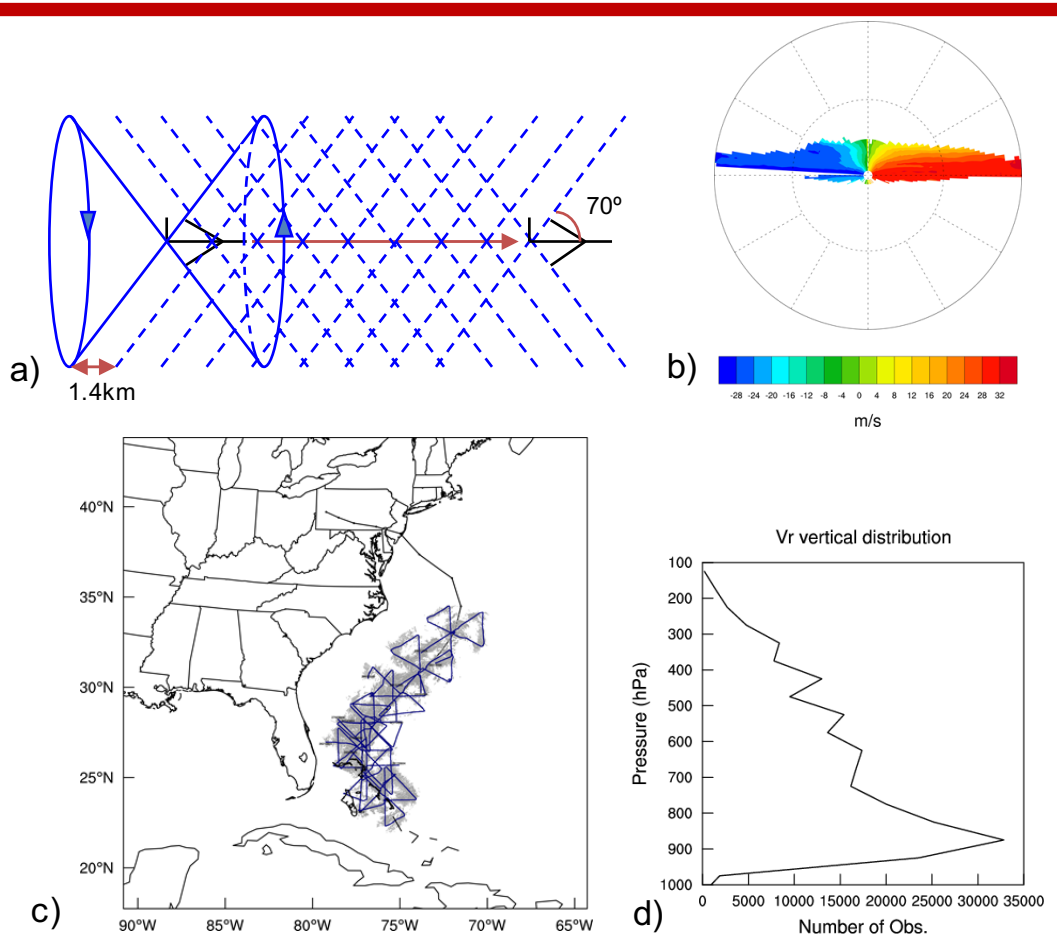
Early R&D for HWRF Hybrid DA

Lu, Wang et al. 2016, QJRMS

- In our previous study, a GSI-based hybrid ensemble-variational data assimilation system for HWRF was developed.
- The new system was applied to assimilate the radial velocity data from Tail Doppler Radar (TDR) onboard NOAA P-3 aircrafts for hurricane initialization and prediction (Lu, Wang et al., 2016).
- Experiments focused on the assimilation of TDR data during 2012-2013 hurricane seasons.



a) Scan scheme of the TDR (Tail Doppler Radar);
b) An example of a Tail Doppler Radar sweep. （Blue for wind towards the radar, red for the wind away from the radar);
c) Flight tracks (blue line) and horizontal distribution of airborne radar data (grey dot) for P3 tail Doppler radar missions during Sandy (2012). The black line is the best track from NHC;
d) Vertical distribution of the number of Tail Doppler Radar data collected during the first NOAA P3 mission of Sandy.

Early R&D for HWRF Hybrid DA

Lu, Wang et al. 2016, QJRMS

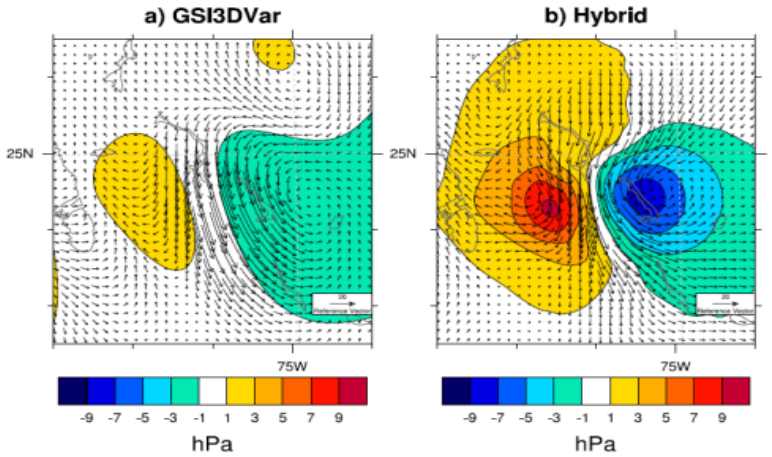


Fig. 8 SLP (shaded) and 1000hPa wind (vector) increments after assimilating the first penetration leg of TDR data. For a) GSI3DVar, b) Hybrid

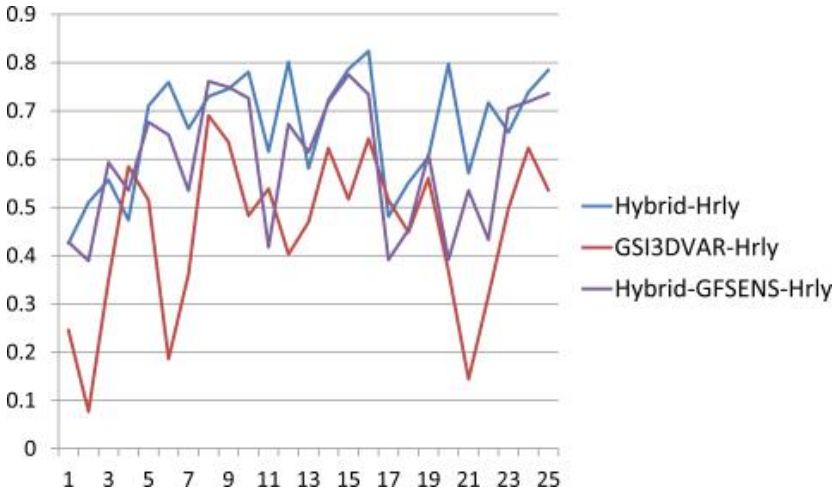


Fig. 15 Correlation coefficient values for all missions during 2012-2013 seasons for Hybrid-Hrly (Blue), GSI3DVar-Hrly (Red) and Hybrid-GFSENS-Hrly (Purple) against HRD composite.

- Results showed that the hybrid system was able to correct both the wind and mass fields in a dynamically and thermodynamically coherent fashion.
- The hybrid system using self-consistent HWRF EnKF ensemble (Hybrid) was found to improve both the analyzed TC structures and forecasts relative to GSI-3DVar and the hybrid ingesting GFS ensemble (Hybrid-GFSENS).
- The impact of the TDR data was dependent on the data assimilation (DA) method.
- Hybrid provided the largest positive impact of the airborne radar data (TDR).

Motivation of Further Development of GSI-based, Continuous Cycling, Dual-resolution, Hybrid EnKF-Var Data Assimilation for HWRF

- Early efforts (Lu, Wang et al. 2016) only explored the hybrid DA system over a small period of the Tropical Cyclone (TC) lifetime which was covered by TDR data.

➢ The system is therefore extended to conduct DA and forecast cycles for the entire life of TC (genesis, rapid intensification, weakening, etc.) assimilating all operational observations in addition to TDR

- Early efforts only explored the hybrid DA system in partial cycling mode.

➢ The system is further developed for end to end, continuous DA cycling (directed moving nest strategy, see slides 6)

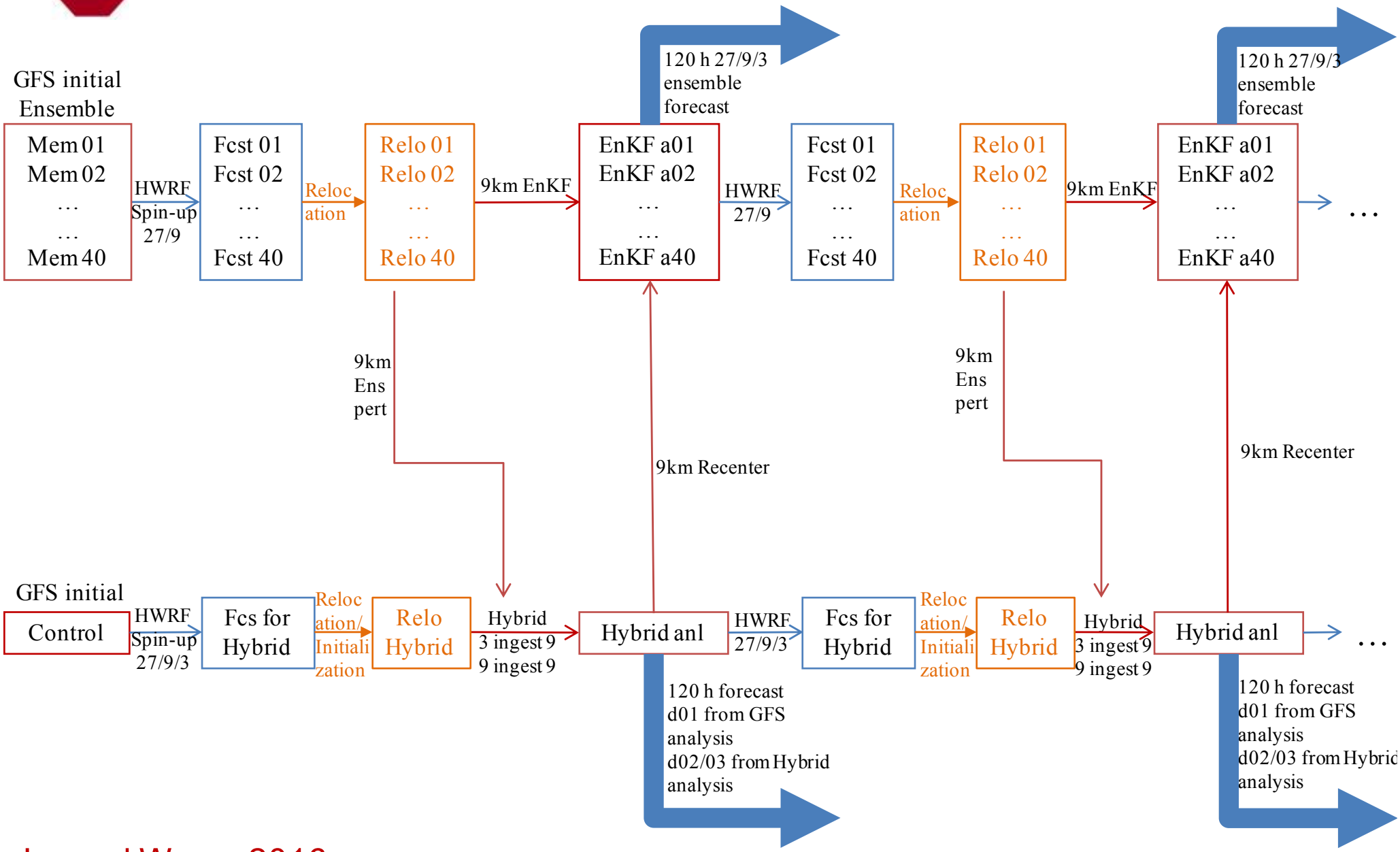
➢ Optimize DA configuration in the context of end to end, continuous DA cycling

a) What's the impact of dual resolution over single resolution hybrid DA?
b) What's the impact of vortex initialization and relocation?
c) What's impact of 3DEnVar vs. 4DEnVar for vortex scale airborne radar observation assimilation?

- Operational HWRF shows "spin-down" issue.

➢ How and why can the newly developed hybrid system help alleviate the "spin-down" issue?

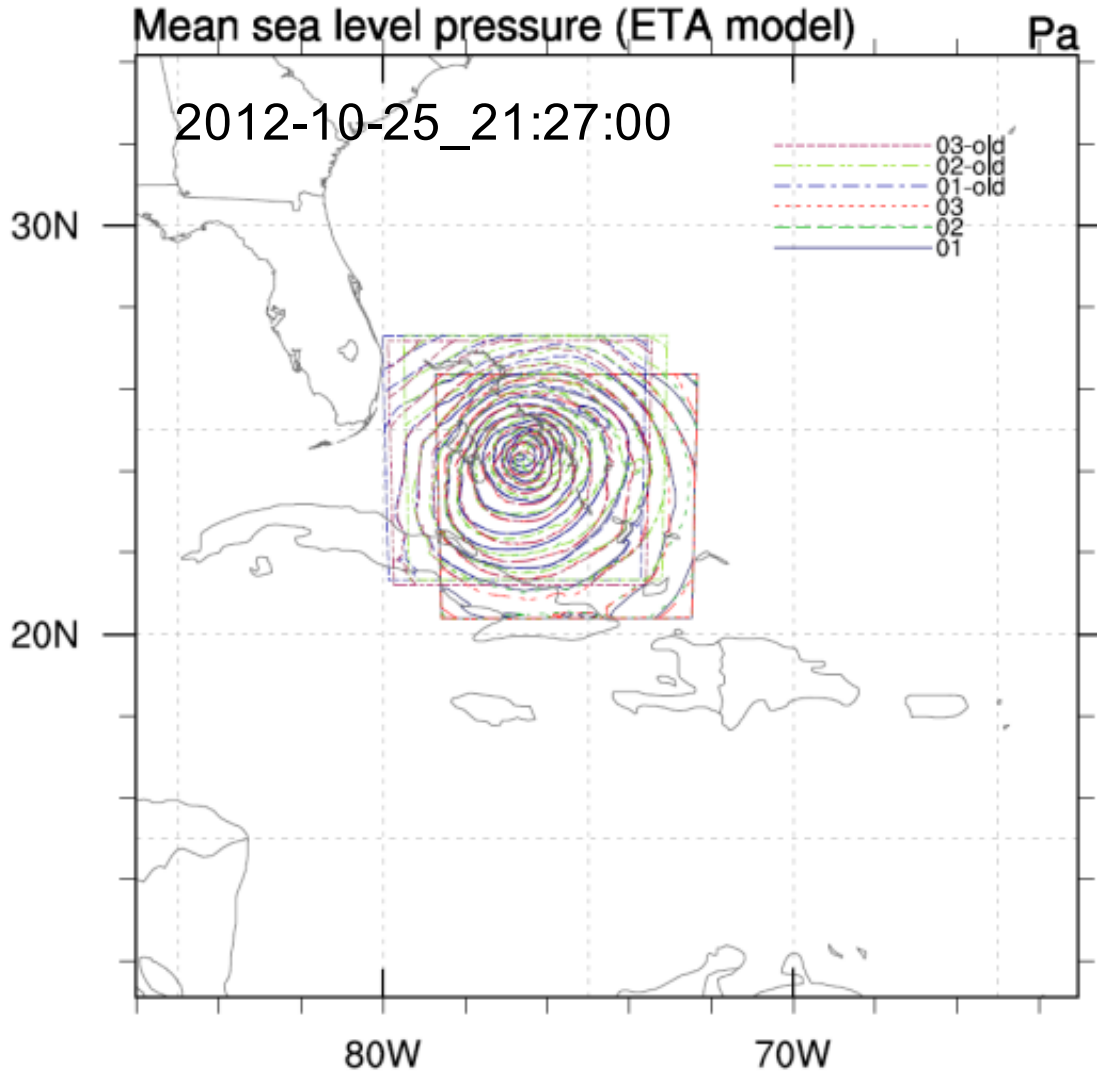
Continuously cycled, Dual-resolution, HWRF hybrid DA system



Lu and Wang, 2016

Directed moving strategy: move ensemble of domains to a same location

- Directed moving strategy: Move ensemble of nests to prescribed locations to solve issue of non-overlapped domains for cycled ensemble DA



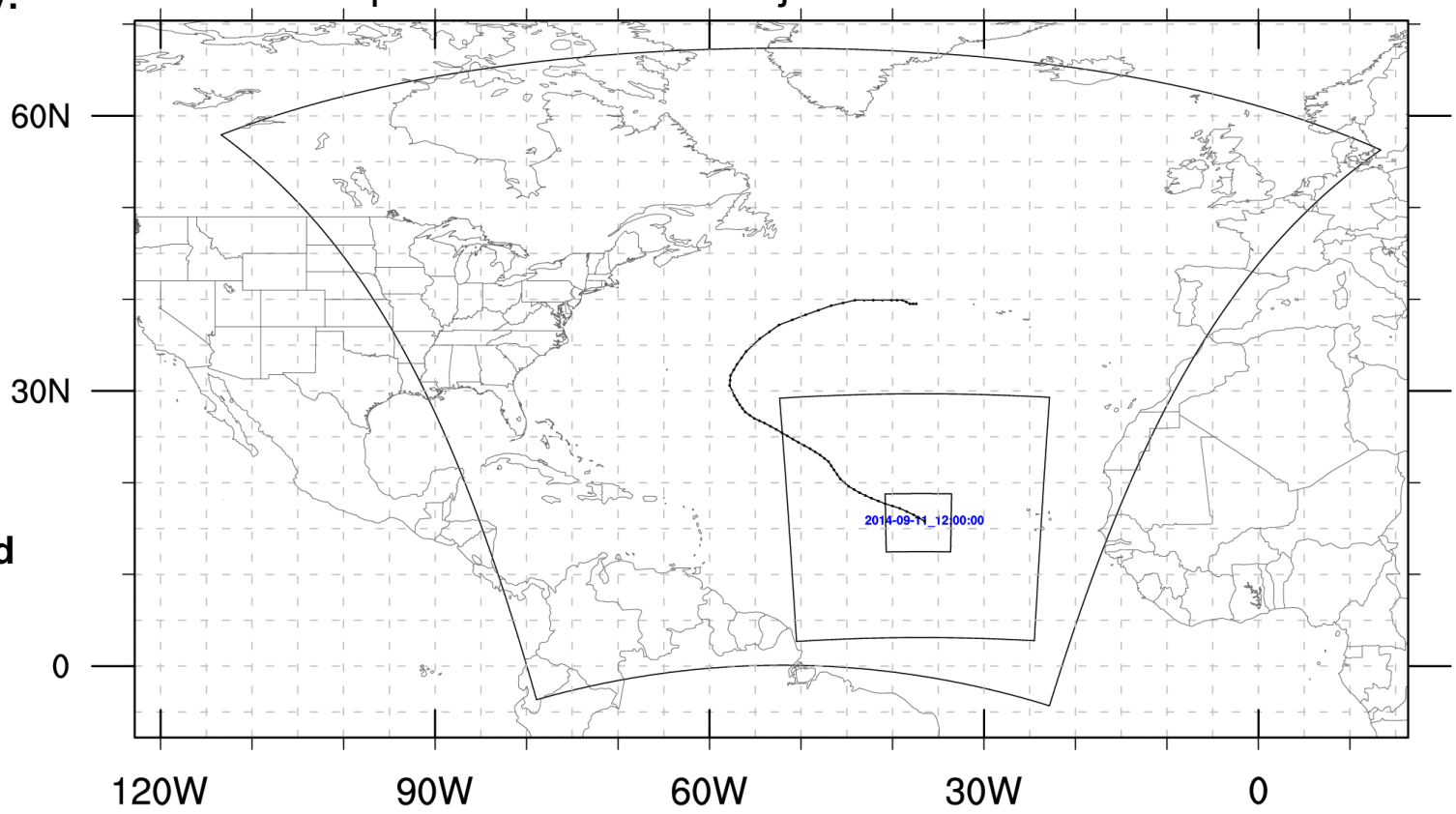
d01:
member 1 with directed moving
d02:
member 2 with directed moving
d03:
member 3 with directed moving

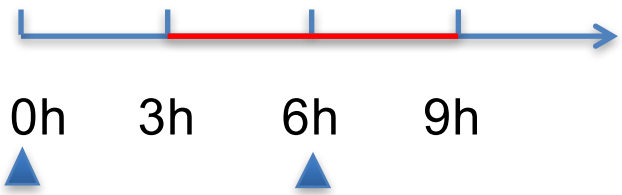
d01-old:
member 1 with storm following
d02-old:
member 2 with storm following
d03-old:
member 3 with storm following

Example of 6-hourly cycling using directed moving nest strategy (Edouard 2014)

- **Directed moving strategy: Move ensemble of nests to prescribed location to solve issue of non-overlapped domains for cycle ensemble DA**
- **Moving nest has capability to move and stop as needed to apply e.g., 4DEnVar, FGAT**
- **Straightforward to extend for e.g. basin scale multiple moving nests implementation**

Note: Example domain size is adjustable.





- **No blending with GFS analysis needed and thus avoid discontinuity.**
- **Simple to implement. No DA code changes needed**
- **Flexibility to decide directed locations (see slide 24~25)**

Experiments for Edouard 2014
Lu and Wang, 2016

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.

Experiments for Edouard 2014

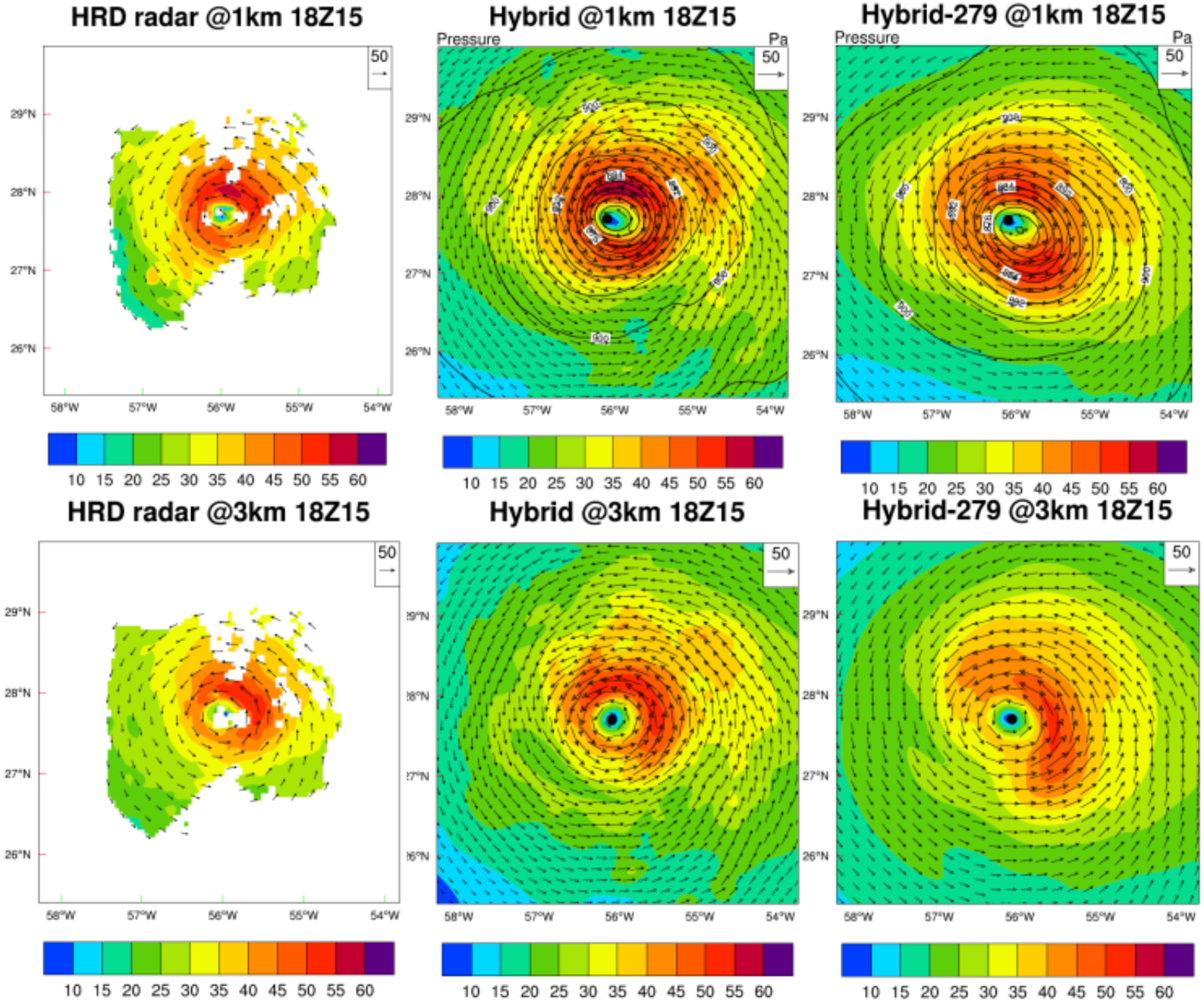
Observations assimilated:

3km domain:
Conventional in-situ data in prepbufr, satellite wind, TDR and tcvital

9km domain:
Conventional in-situ data in prepbufr, satellite wind, TDR and tcvital
Satellite radiances

Impacts of Dual Resolution Hybrid

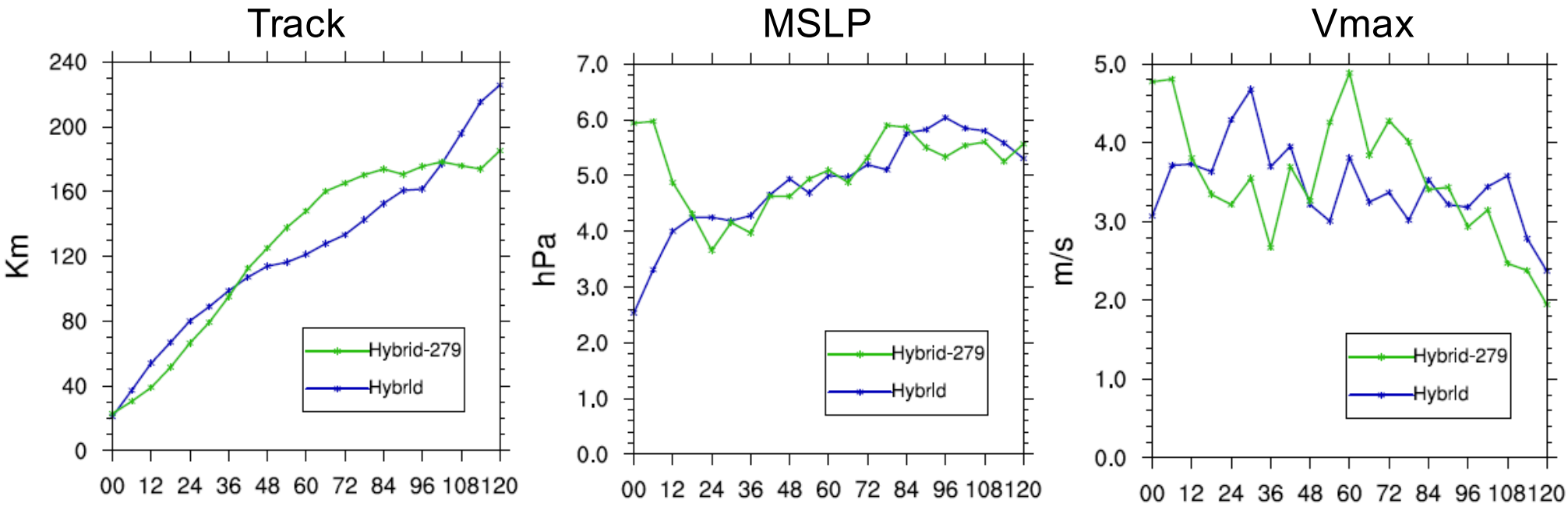
analyzed Edouard structure @2014091518



- The horizontal wind pattern generated by Hybrid (dual resolution) fits the HRD wind analysis better than Hybrid-279 (coarser, single resolution).

Impacts of Dual Resolution Hybrid

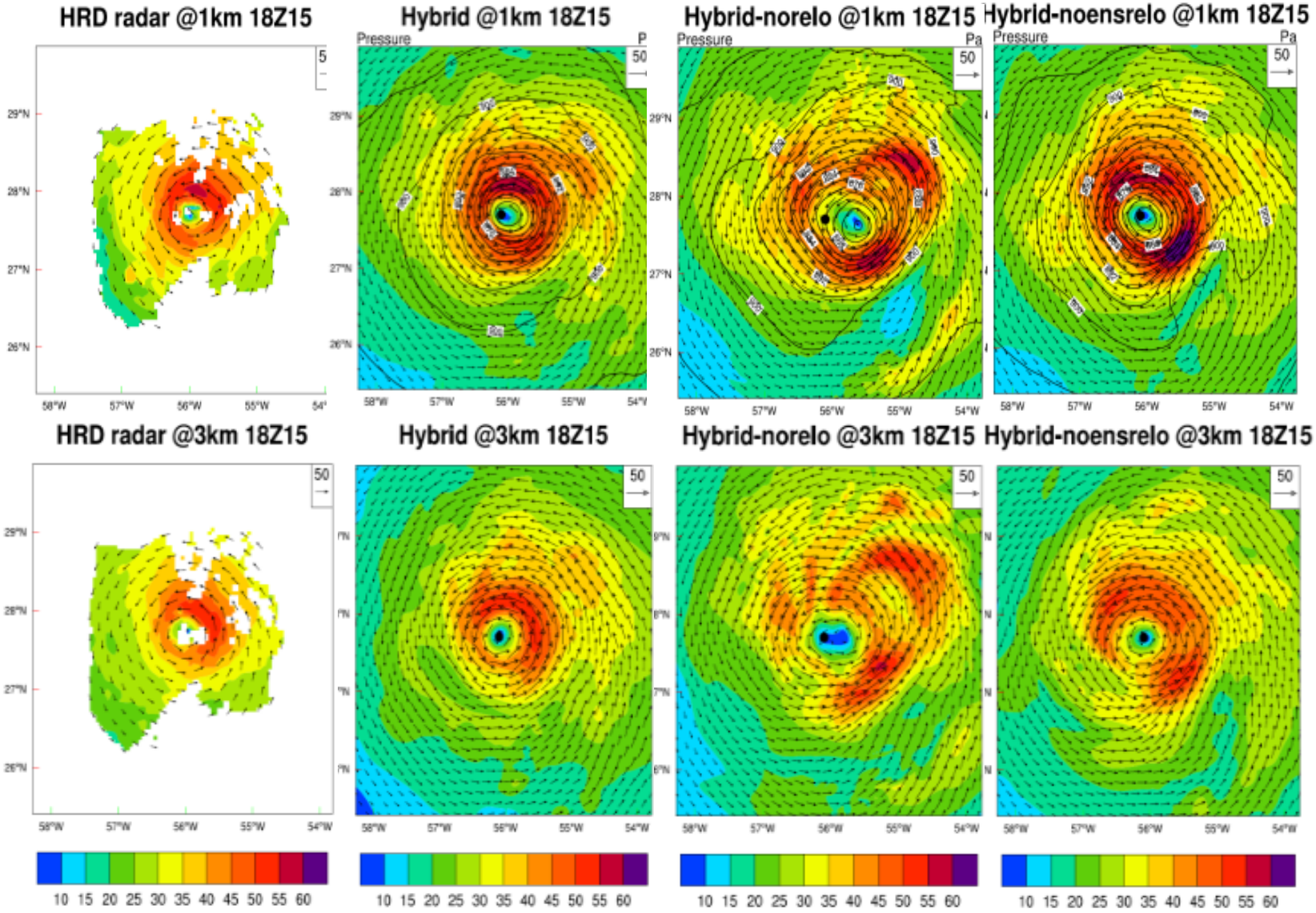
mean forecast errors for all cycles (Lu and Wang, 2016)



- The Vmax and MSLP forecasts in Hybrid (blue, dual reso.) are improved for the first 12~18 hours compared to those in Hybrid-279 (green, coarser single resolution.).
- Together with the previous structure analyses, Hybrid (dual resolution) is better than Hybrid-279 (coarser single resolution).
- This result shows the positive impact of using a high resolution control analysis and forecast through dual resolution hybrid DA.

Impacts of vortex initialization and ensemble relocation

analyzed Edouard structure @2014091518

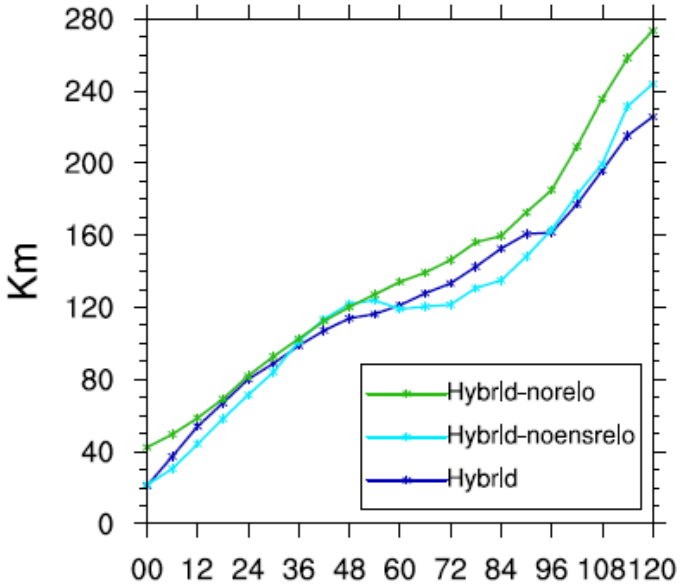


- There is a large location error in Hybrid-norelo.
- Storm location in Hybrid-noensrelo is more accurate than that in Hybrid-norelo.
- Hybrid-noensrelo still worse than Hybrid. The wind field in Hybrid-noensrelo is spuriously strong and pressure field shows a spurious dipole feature

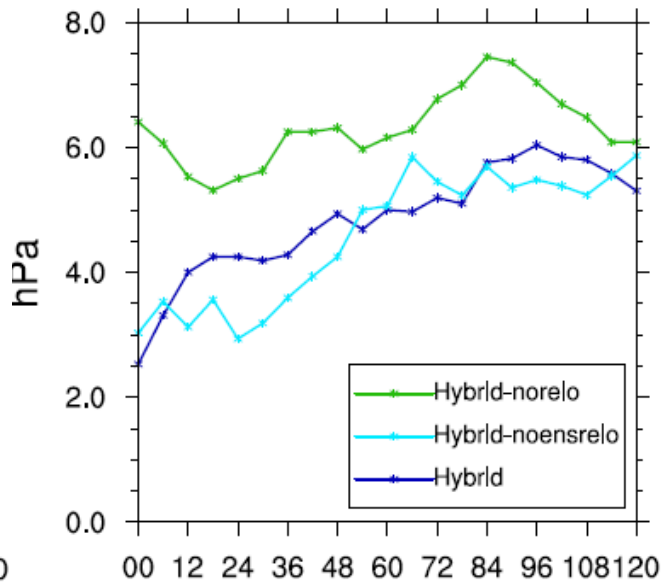
Impacts of vortex initialization and ensemble relocation

mean forecast errors for all cycles (Lu and Wang, 2016)

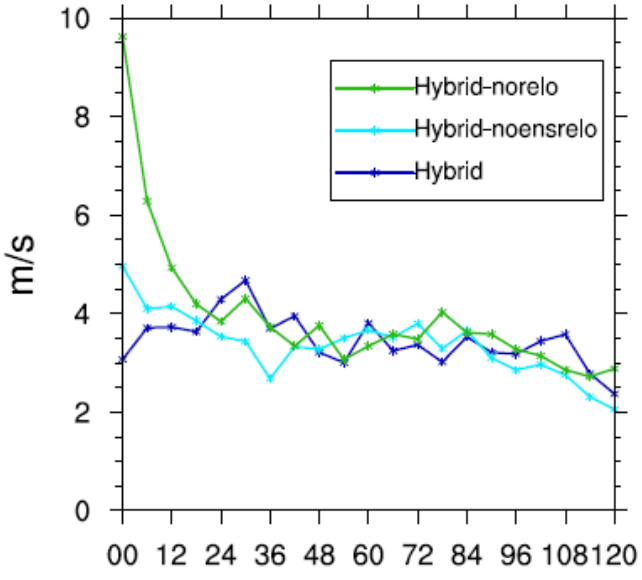
Track (km)



MSLP (hPa)

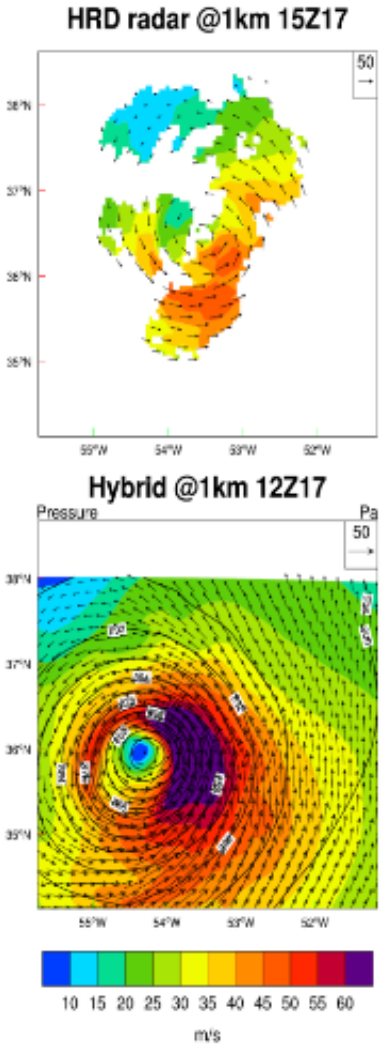


Vmax (m/s)

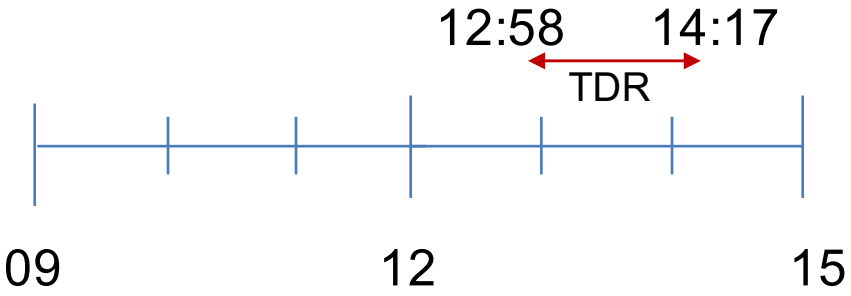


- Hybrid-norelo (green) performs worst.
- Hybrid-noensrelo (light blue) is better than Hybrid-norelo, but still worse than Hybrid (dark blue) especially for Vmax forecasts at earlier lead times.
- Together with the previous structure analyses, Hybrid with both ensemble relocation and control vortex relocation/initialization improves the forecasts compared to both Hybrid-noensrelo and Hybrid-norelo.

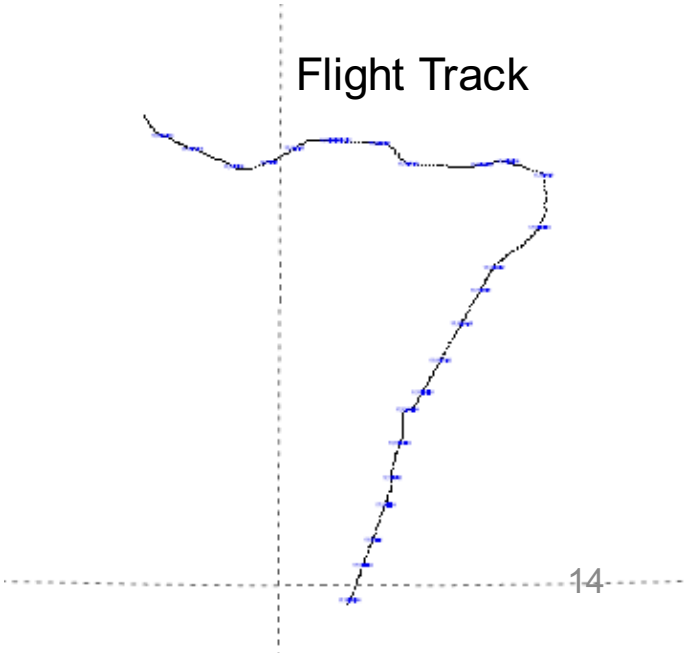
Motivation of 4DEnVar DA for vortex scale observation assimilation



- Spuriously large wind maximum analyses in Hybrid with 3DEnVar are found in the last two TDR-involved cycles.
- Edouard is going through complicated rapid-changing eyewall replacement process.
- TDR coverage is very brief and unevenly distributed over the 6-hour window (e.g. TDR covers 12:58~14:17 for cycle 24 valid at 12Z).
- Methods (4DEnVar) considering rapid error evolution during the 6 hr window (rather than 3DEnVar over 6-hr window) is needed.

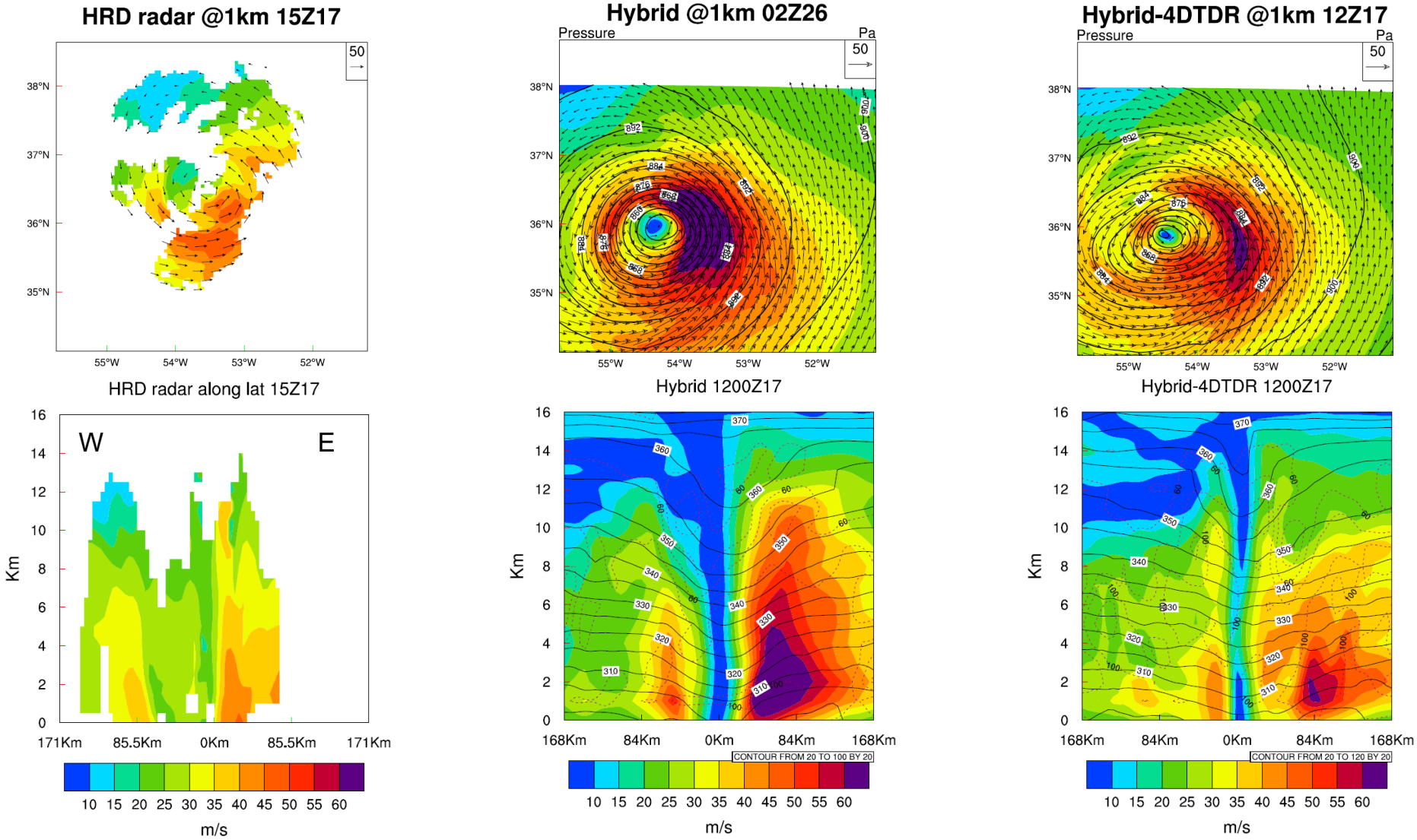


Valid at 12 UTC, Sep 17th 2014



Impacts of 4DEnVar for vortex scale observation assimilation

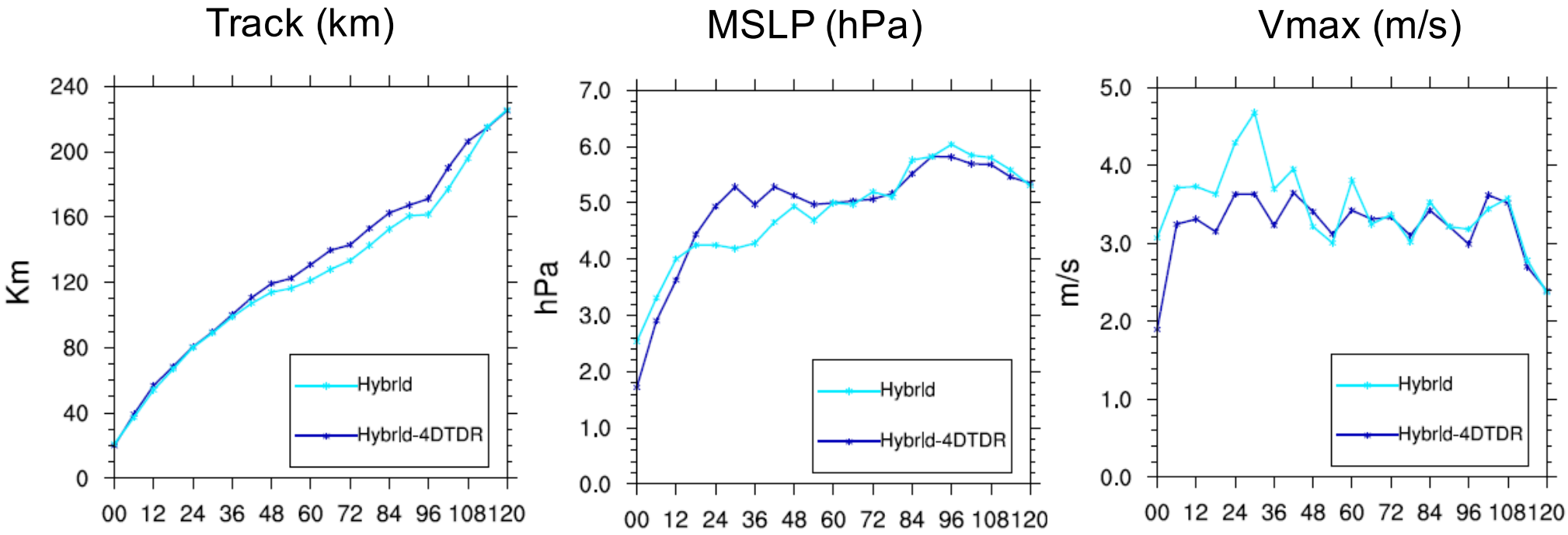
analyzed Edouard structure @2014091712



- Using 4DEnVar, the spurious wind maximum was reduced and the wind pattern is more consistent with HRD radar composite as compared to 3DEnVar

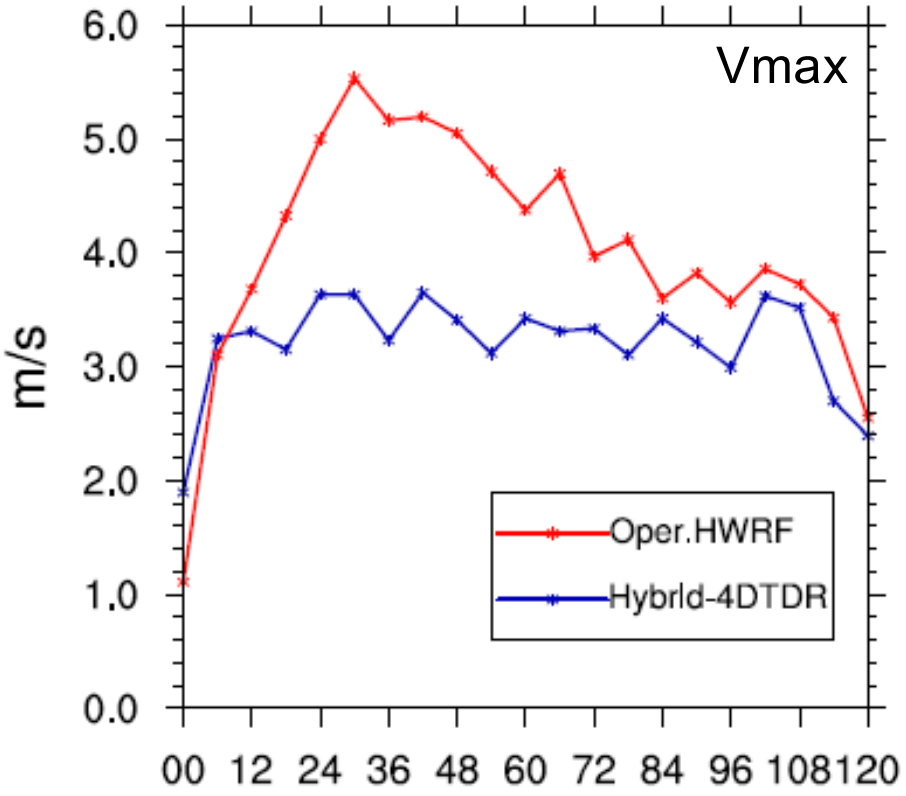
Impacts of 4DEnVar for vortex scale observation assimilation

mean forecast errors for all cycles (Lu and Wang, 2016)



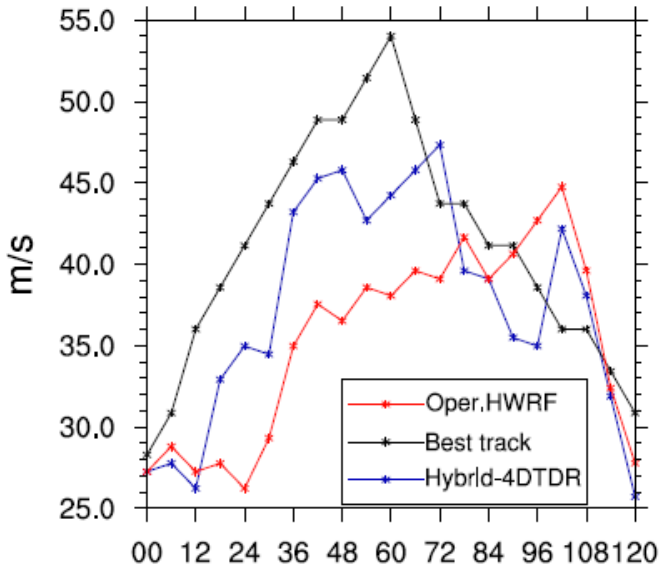
- Forecasts shows that the intensity forecasts at early lead times were improved in Hybrid-4DTDR (dark blue) compared to those in Hybrid (light blue, 3DEnVar).
- Together with the previous structure analyses, Hybrid-4DTDR, which used 4DEnVar in TDR-involved cycles, is better than Hybrid using purely 3DEnVar especially for Vmax/MSLP forecasts at early lead times.

Alleviation of the "spin-down" issue relative to operational HWRF

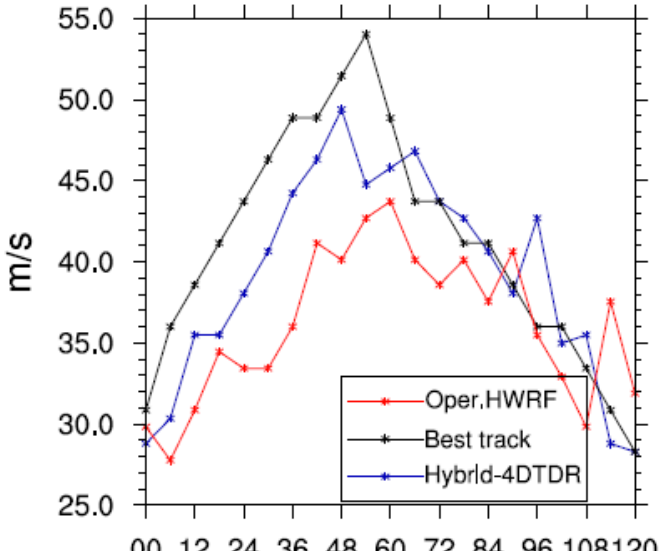


- Hybrid-4DTDR improves intensity forecast relative to operational HWRF during the intensification of Edouard until it reached the maximum intensity.

Cycle 10 @ 2014091400 UTC



Cycle 11 @ 2014091406 UTC

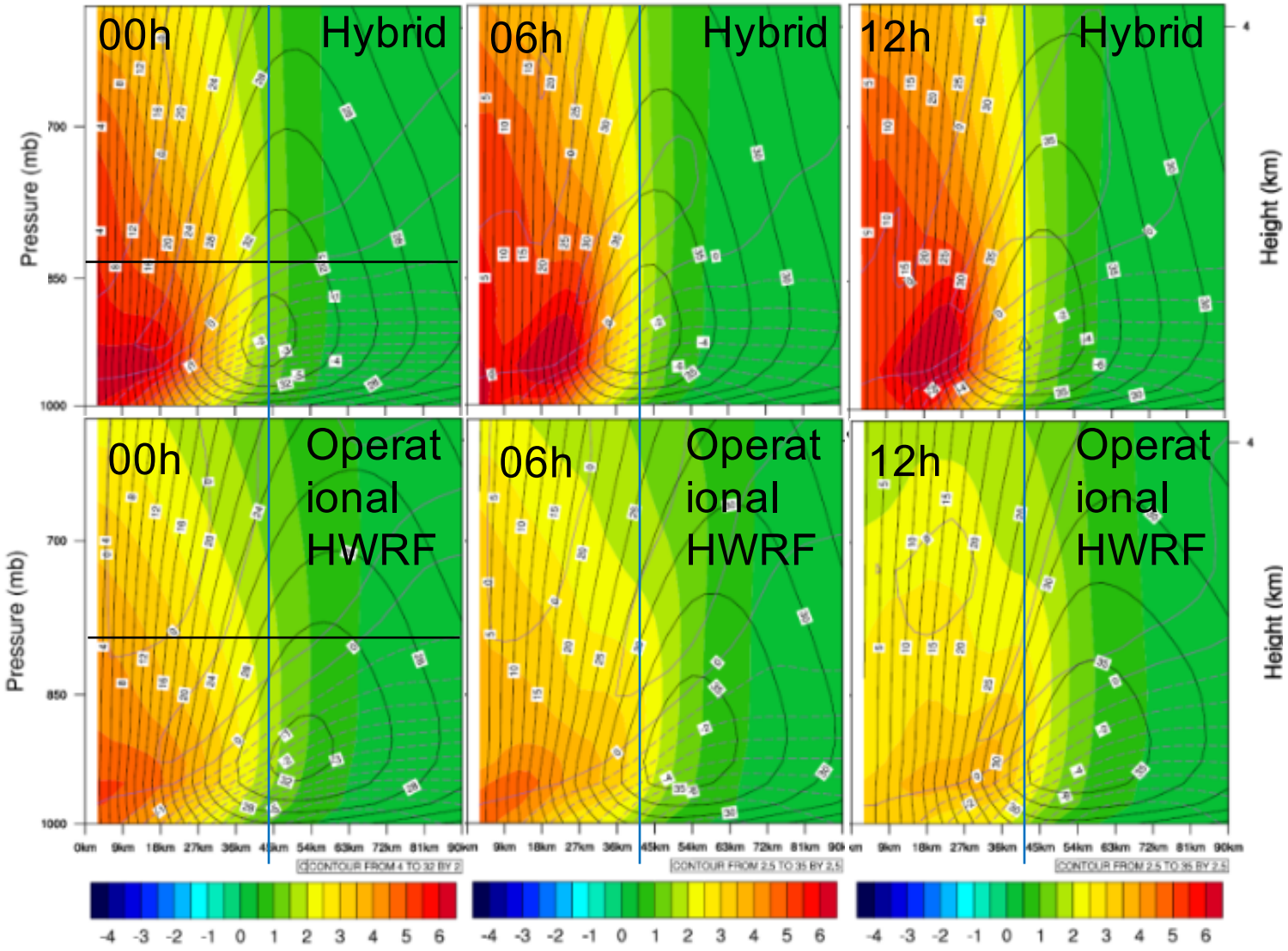


- The improvements in the intensity forecasts from Hybrid-4DTDR are due to the alleviation of the "spin down" issue presented in operational HWRF during the intensification of Edouard.

Why new hybrid system alleviate the “spin-down” issue ?

- Compared to operational HWRF, Hybrid analysis has a stronger Inertial Stability, smaller RMW, stronger tangential wind and shallower inflow layer.
- Stronger Inertial Stability -> stronger resistance to radial inflow-> stronger updraft-> stronger secondary circulation-> intensification (Holland and Merrill 1984)
- This explains why Hybrid analysis helps alleviate the “spin-down” issue

Averaged azimuth mean Inertial Stability (Shaded), Radial wind (Grey contour) and Tangential wind (Black contour) during all Intensifying Stage (Vmax change > 10kt/12h; Rogers, et al. 2013)



Summary

- GSI-based, continuously cycled, dual resolution, hybrid EnKF-Var DA system with new directed moving nest strategy, assimilating all operational observations for HWRF is developed.

- Experiments with Edouard with 6-hourly, continuous, end to end DA cycling suggest:
  - ➢ High resolution analysis produced through dual resolution hybrid DA improves structure analysis and intensity (Vmax and MSLP) forecasts.
  - ➢ Vortex relocation/initialization integrated with 6-houlry Hybrid DA improves forecasts.
  - ➢ Using 4DEnVar assimilation in TDR-involved cycles improves the intensity forecasts for early lead times compared to using 3DEnVar assimilation. Comparison of 4DEnVar and hourly DA is ongoing.
  - ➢ The new hybrid system improves MSLP and Vmax forecasts compared to operational HWRF especially during intensification period through alleviation of spin down issue.
  - ➢ Further diagnostics suggests the spin-down issue is alleviated by better analyzed storm structures by Hybrid. During the intensification stage of Edouard, the stronger inertial stability and smaller RMW are more consistent with the characteristics of an intensifying storm than operational HWRF.

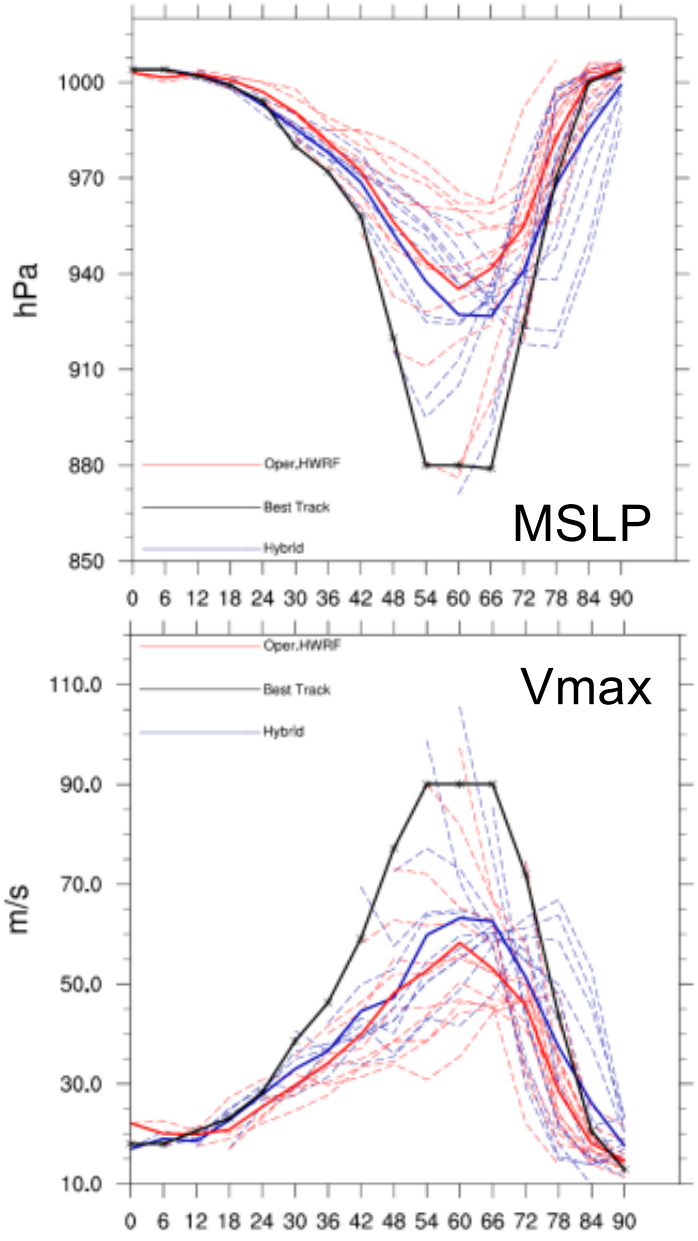
Ongoing & future Work

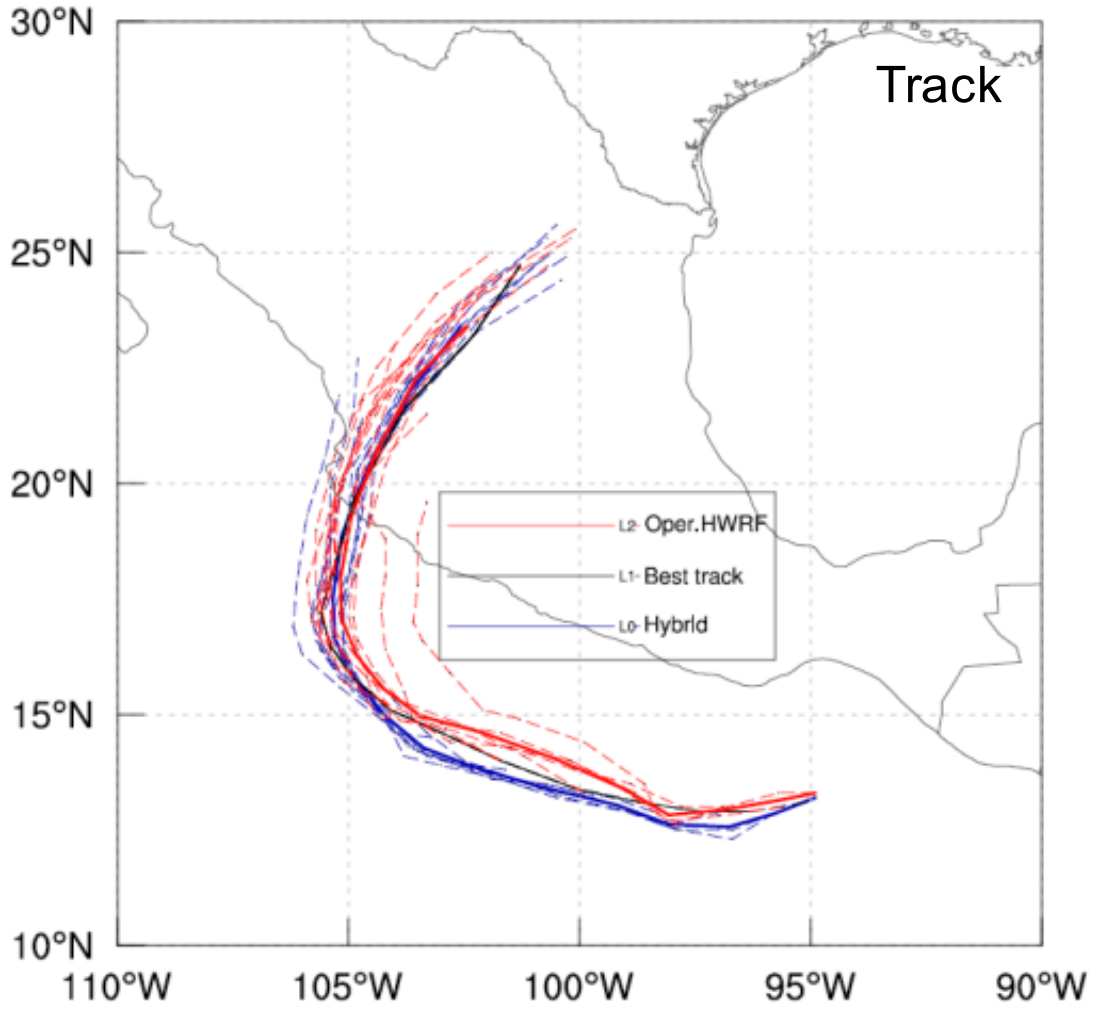
- Continue the exploration of and understanding the differences of various system configurations (e.g. 4DEnVar vs hourly DA vs 4DEnVar+IAU, etc.).

- Optimize the usage of and explore the impact of other airborne and spaceborne observations (P3, GIV radar, dropsonde, flight level, SFMR, HIRAD, AMV, etc.) using the new system.

- Implementation and conducting research of the new hybrid system for future modeling system (e.g. basin-scale HWRF with multiple moving nests, selected NGGPS model, etc.)

2015 near real time results (Hurricane Patricia)





- 2015 near real time experiments still showed better intensity forecasts during the RI of Patricia in comparison with the operational HWRF.