A New Dynamical Vortex Initialization Scheme with Warm Model Startup for Real-Time Forecasts of TCs

Yuqing Wang and Dong-Hyun Cha

International Pacific Research Center

University of Hawaii at Manoa, Honolulu, USA

HFIP Teleconferece Presentation

July 24, 2013

Outline

- An overview on vortex initialization for TC models
- A new dynamical vortex initialization (DVI)
- A Real-time Forecasting System for WNP TCs
- Hindcast results for 2010 and 2011
- Several case studies
- Preliminary results from HWRF
- Future developments

TC Vortex Initialization

Bogus Vortex

- Bogus vortex is constructed by inserting an analytical vortex structure into the global/regional analysis fields at the initial forecast time.

- Simple; assumed hydrostatic, gradient wind, and thermal wind balances; TC intensity matched the observed.
- Initial adjustments with model dynamics and physics; arbitrary horizontal/vertical vortex structure, without the use of any information of the environment the TC is embedded.

(e.g., Ueno 1989; Leslie and Holland 1995; Wang 1998; Ma et al. 2007; Kwon and Cheong 2010)

TC Vortex Initialization

Variational Bogus Data Assimilation (BDA)

- BDA uses variational data assimilation with synthetic observations of a TC vortex that closely matches the observed TC intensity and structure.
- The TC is dynamically balanced and more consistent with model physics.
- Variational data assimilation generally uses simplified (linearized) model physics which are quite nonlinear; observations in TC core are often rare and the synthetic data are just better than nothing since few observations.

(e.g., George and Jeffries 1994; Zou and Xiao 2000; Davidson and Weber 2000; Pu and Braun 2001; Zhang et al. 2007; Wang et al. 2008)

TC Vortex Initialization

Dynamical vortex initialization (DVI)

DVI – Method 1

- Axisymmetric vortex is spun up with the axisymmetric version of the 3D forecast model (Kurihara et al. 1993) or a different 3D model (Hendricks et al. 2011).
- More realistic 3D TC structure and dynamical balance; wavenumber-one asymmetry as beta-gyres is added from barotropic model integration.
- Still initial adjustment issue; no any information of the environment the TC is embedded; cold model startup.

(e.g., Kurihara et al. 1993, 1995; Bender et al. 1993; Peng et al. 1993; Hendricks et al. 2011; 2013).

TC Vortex Initialization

Dynamical vortex initialization (DVI)

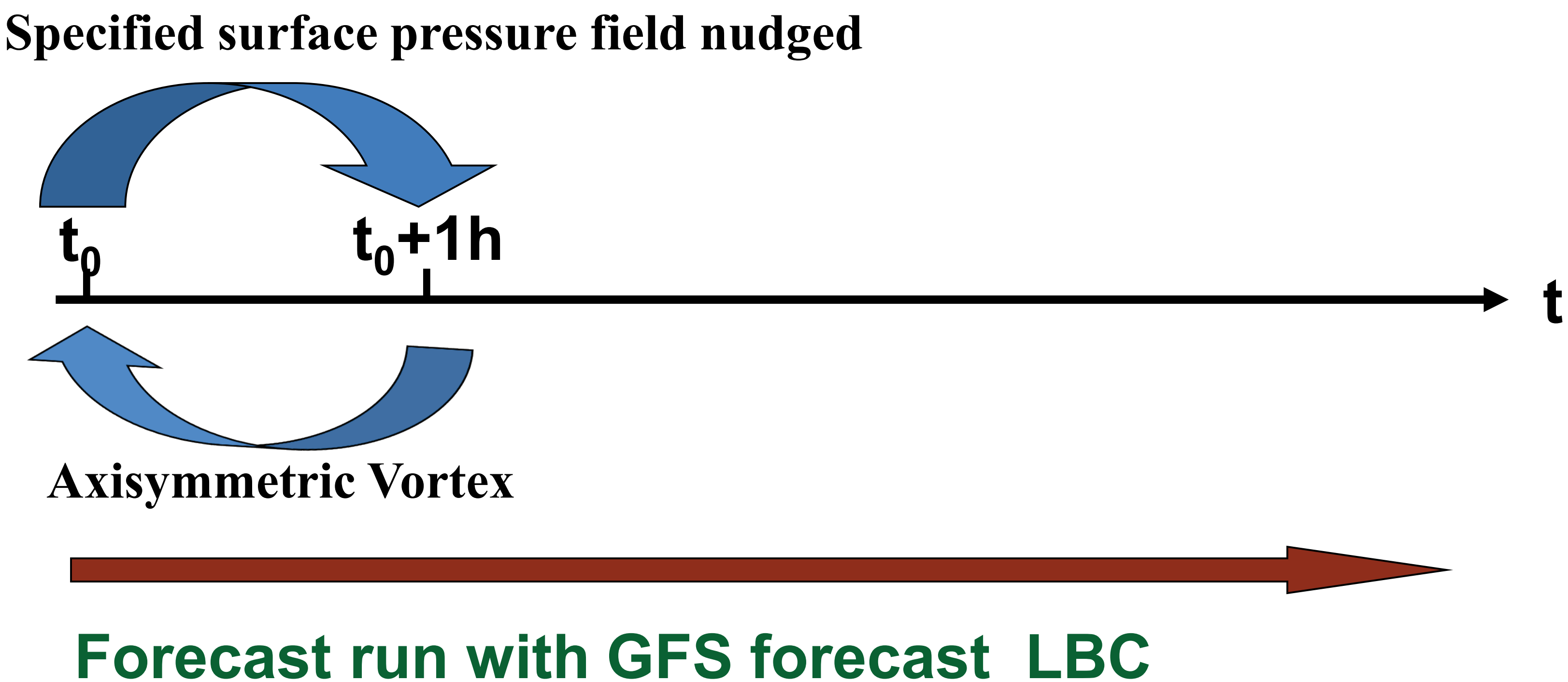
DVI – Method 2

- Axisymmetric vortex is spun up with the 3D forecast model by repeated model integrations with specified surface pressure nudged (Nguyen and Chen 2011).
- Assumedly more dynamically balanced; including the environmental effect on the spin-up of the axisymmetric TC vortex structure.
- Still initial adjustment issue (1h); no asymmetric structure information considered; cold model startup.

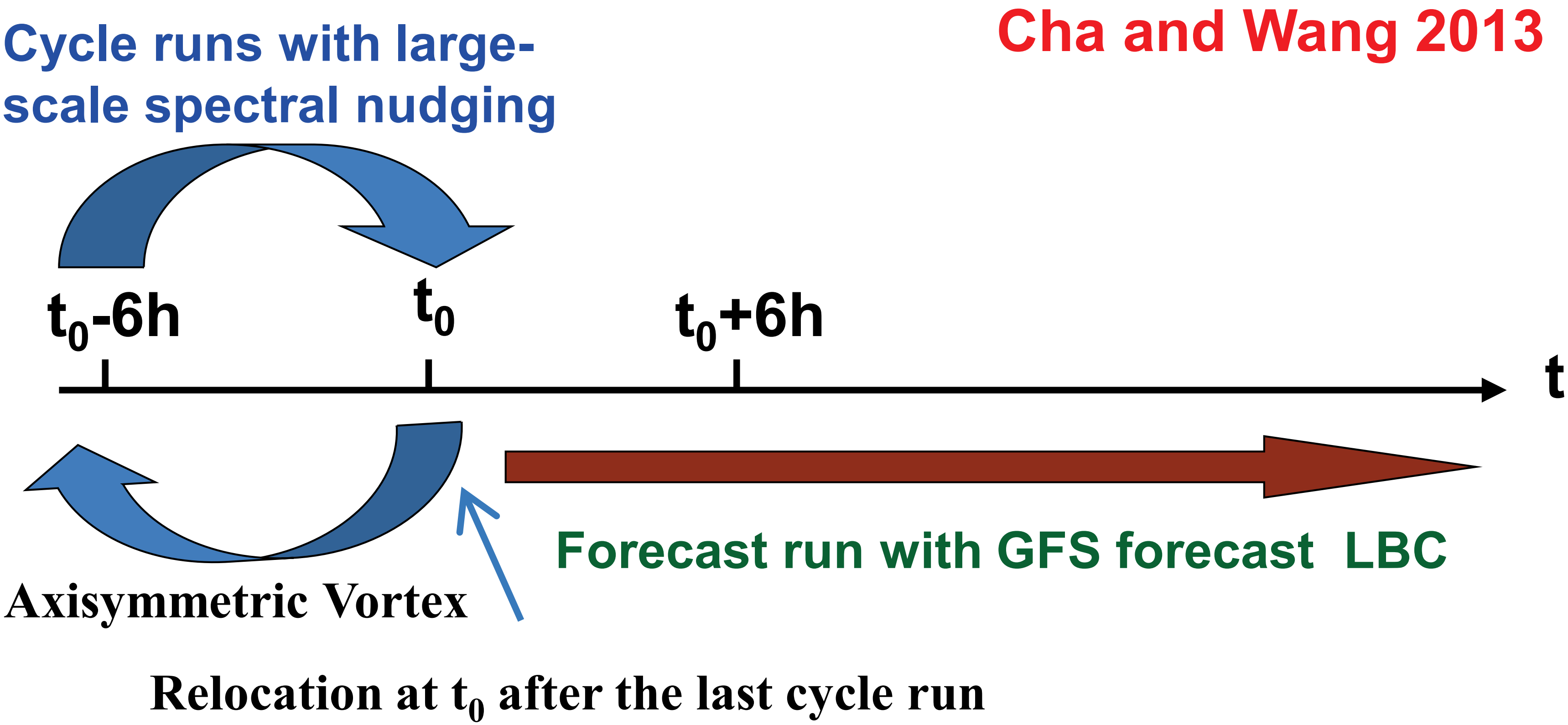
Any innovational Ways to improve these?

DVI – Method 2 (cycle runs)

- Initial adjustment issue because of 1h forward integration;
- No asymmetric structure information considered;
- Cold model startup.



A New Dynamical Vortex Initialization

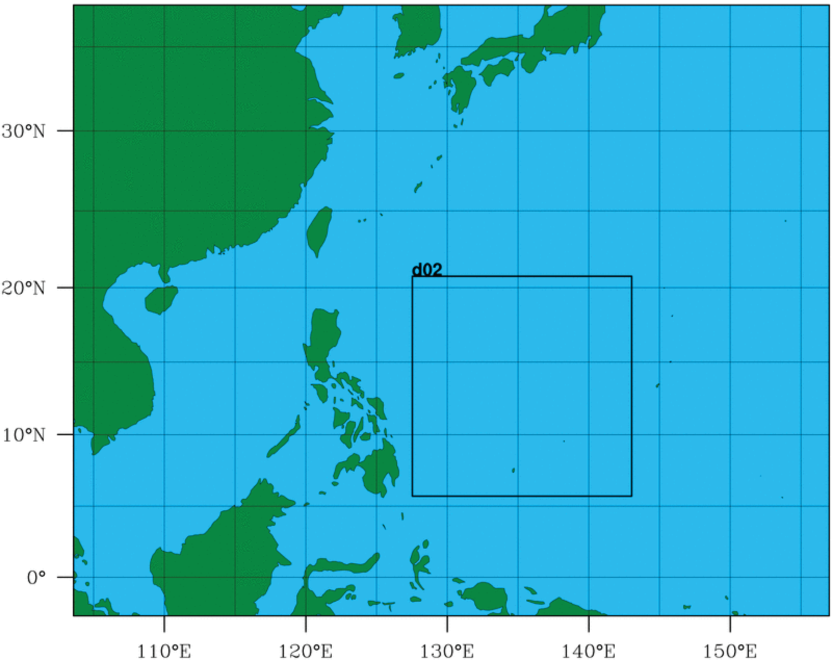


- Dynamical balance (after 6 –h spin-up)
- Asymmetric structure forced by the environment
- Warm model physics startup (after 6-h integration)

Implementation in WRF-ARW model

Cycle Runs

Domains



Domain center
TC lat =< 20°N : Real TC lat +5°, & lon -5°
TC lat > 20°N : Real TC lat +5°

Model configuration

Model Configuration		
Model Prototype	WRFV3.3	
Horizontal grids (resolution)	DM1 311X251 (18km)	DM2 271X271 (6km)
Vertical layers(P top)	28 levels (50hPa)	28 levels (50hPa)
Time-step	90s	30s
CPS	KF	None
PBL	YSU	
MP	WSM6	
Radiation	Dudhia / RRTM	
Surface	NOAH	
Spectral nudging	U, V, T	No
Moving nesting	No	No
Forcings (Initial, Boundary)	NCEP GFS analysis data (0.5degree)	
Initial time	-6h from the initial time of forecast run	
Simulation period	6hs	

Dynamical Vortex Initialization (DVI)

- Weak initial TC vortex can be dynamically enhanced by the repeated 6 h cycle runs using high-resolution mesoscale model.
- Each cycle run is initialized at t_0-6h and integrated for 6 h to t_0 using the real-time GFS analysis as the initial and boundary conditions with large-scale spectral nudging.

Cycle runs

$$F^N(x,y,z,t_0-6)=$$

$$\underbrace{F_E(x,y,z,t_0-6)+F_V^{as}(x,y,z,t_0-6)}_{\textbf{Environment part and asymmetric vortex of GFS}}+\overbrace{\omega F_V^{ax}(x,y,z,t_0-6)+(1-\omega)F_V^{ax,N-1}(x+dx,y+dy,z,t_0)}^{\textbf{Spun-up axisymmetric vortex}}$$

F^N : *Total part at* t_0-6 *in Nth cycle*

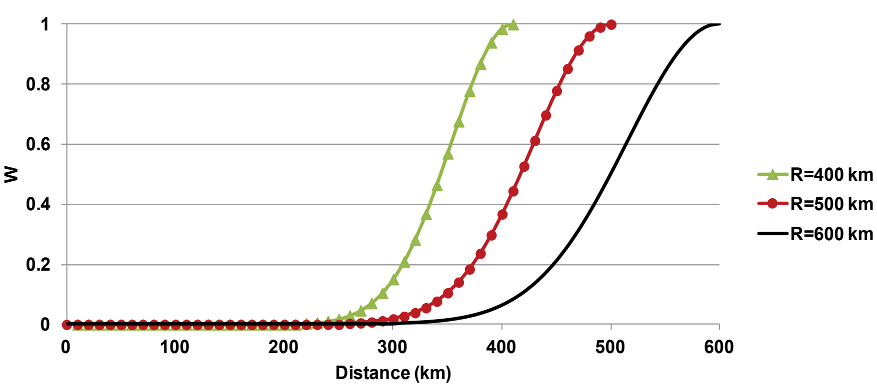
F_E : *Environmental part at* t_0-6

F_V^{as} : *Asymmetric vortex part of GFS at* t_0-6

F_V^{ax} : *Axisymmetric vortex part of GFS at* t_0

$F_V^{ax,N-1}$: *Axisymmetric vortex part of* $N-1$*th cycle run*

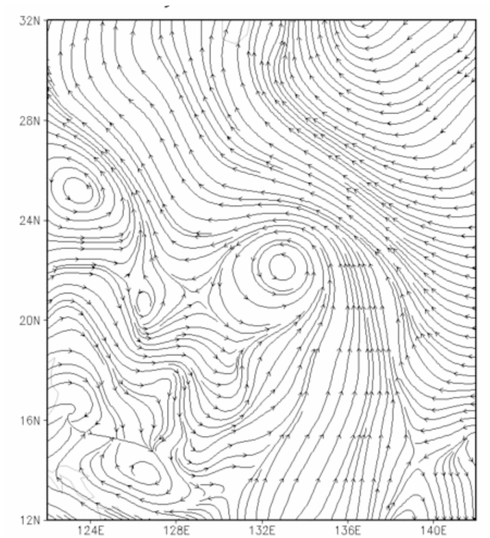
Merging weighting function (ω)



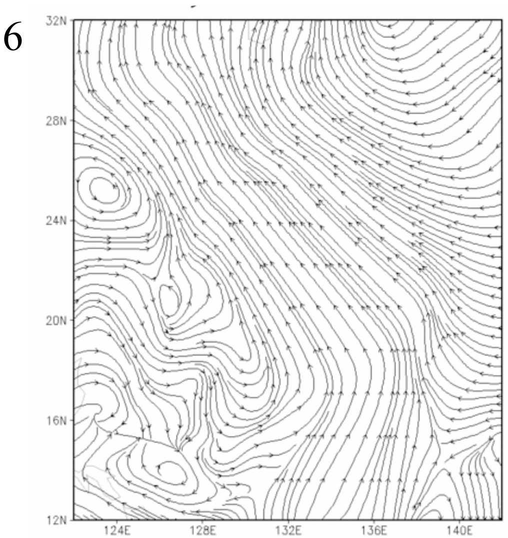
Initial field separation

500 hPa Streamline

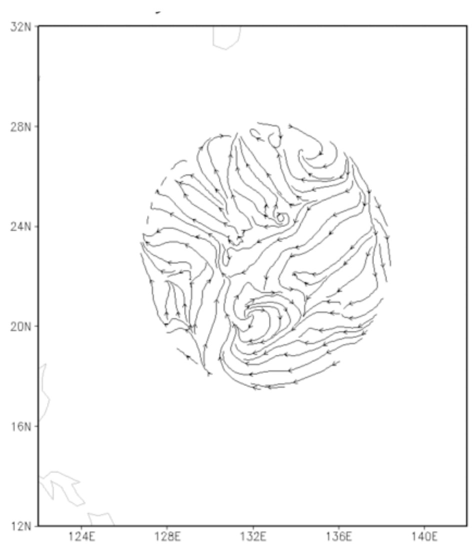
F^{t_0-6}



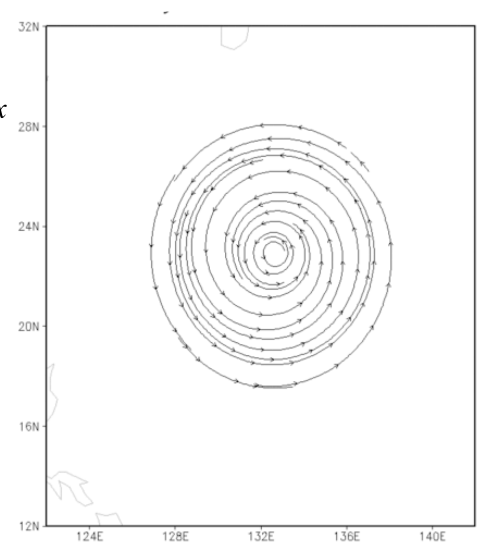
$F_{env}^{t_0-6}$



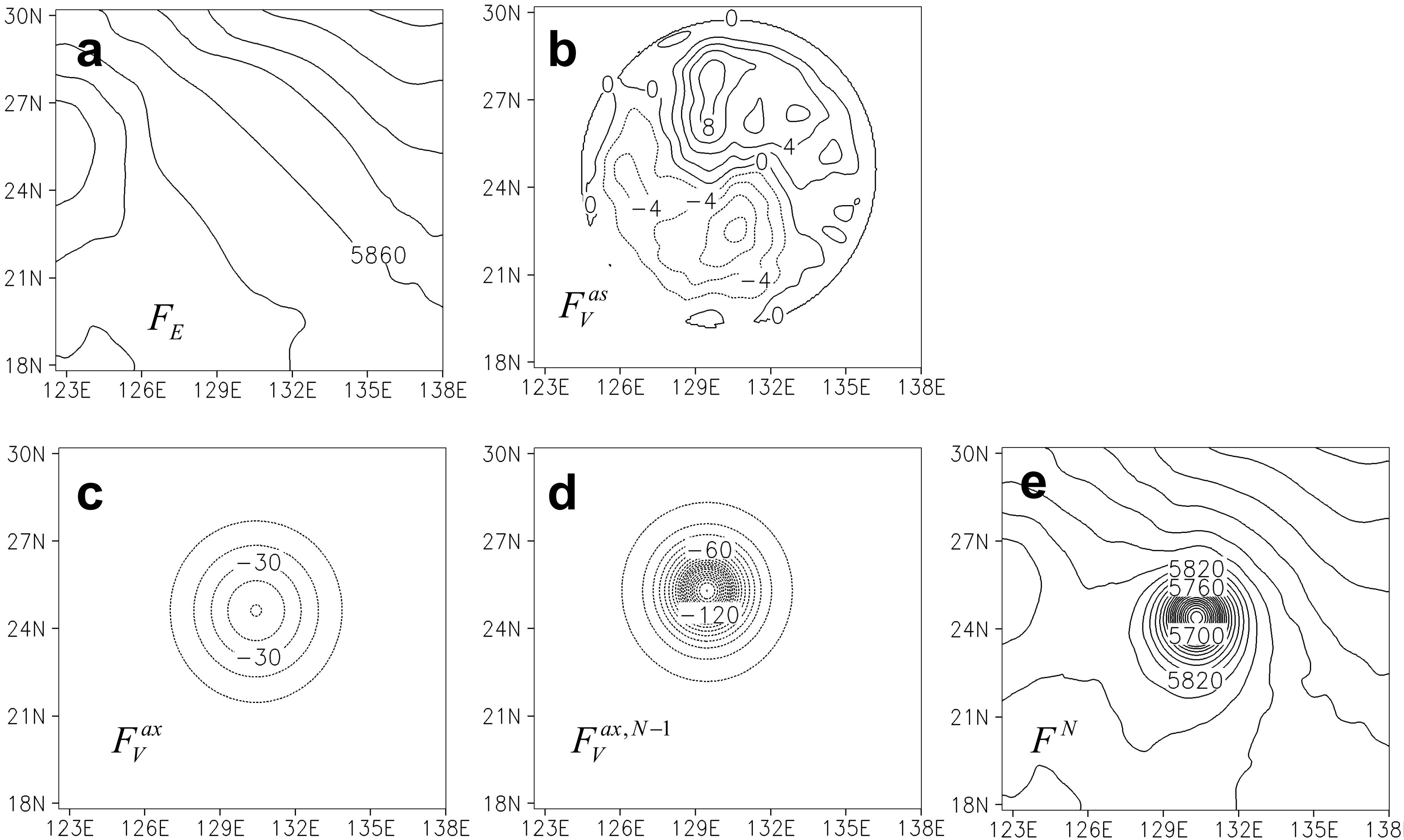
$F_{vor_{as}}^{t_0-6}$



$F_{vor_{ax}}^{t_0}$



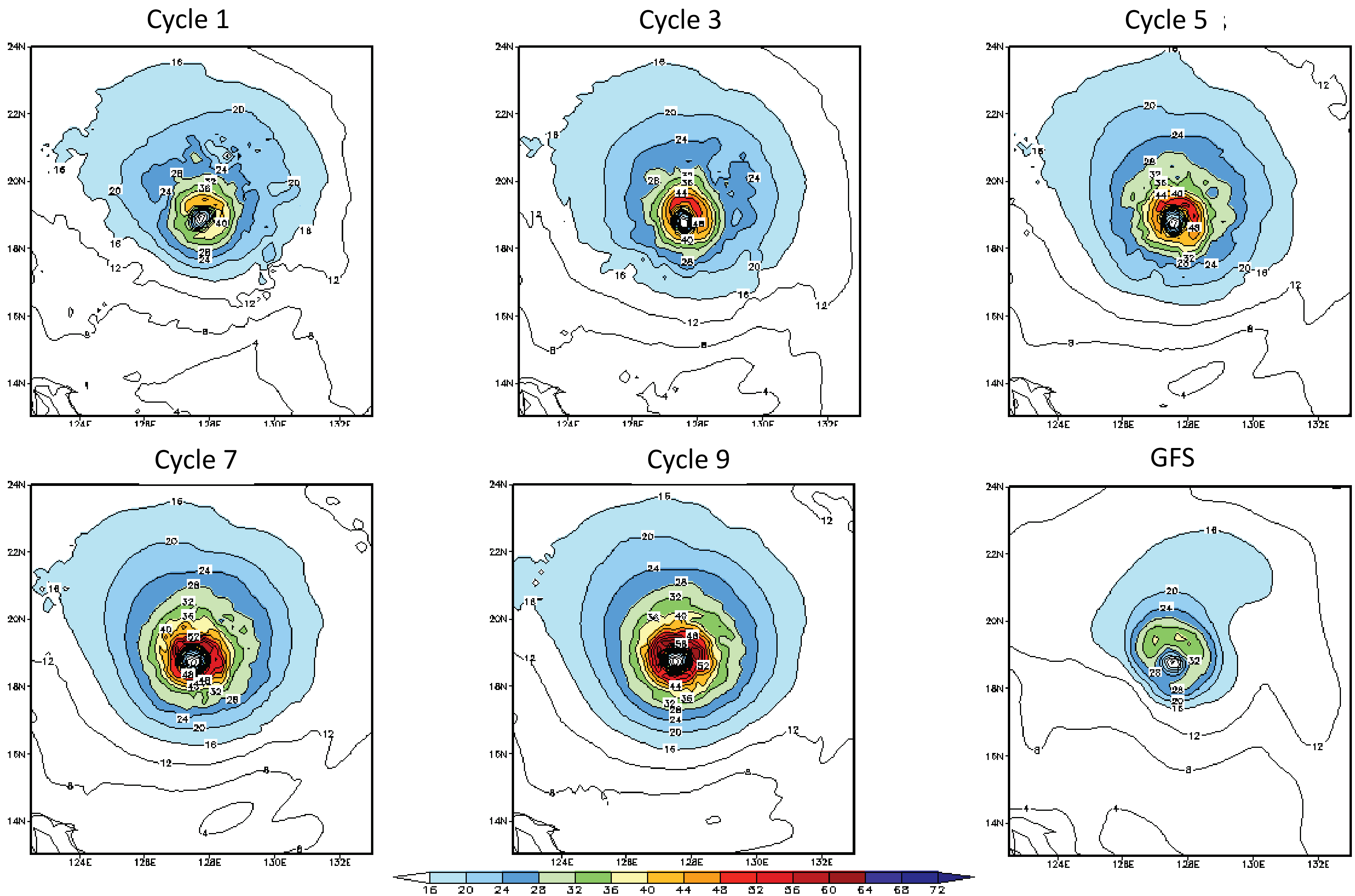
$$F^{t_0-6} = F_{env}^{t_0-6} + F_{vor_{as}}^{t_0-6} + F_{vor_{ax}}^{t_0}$$



500 hPa geopotential height (gpm)

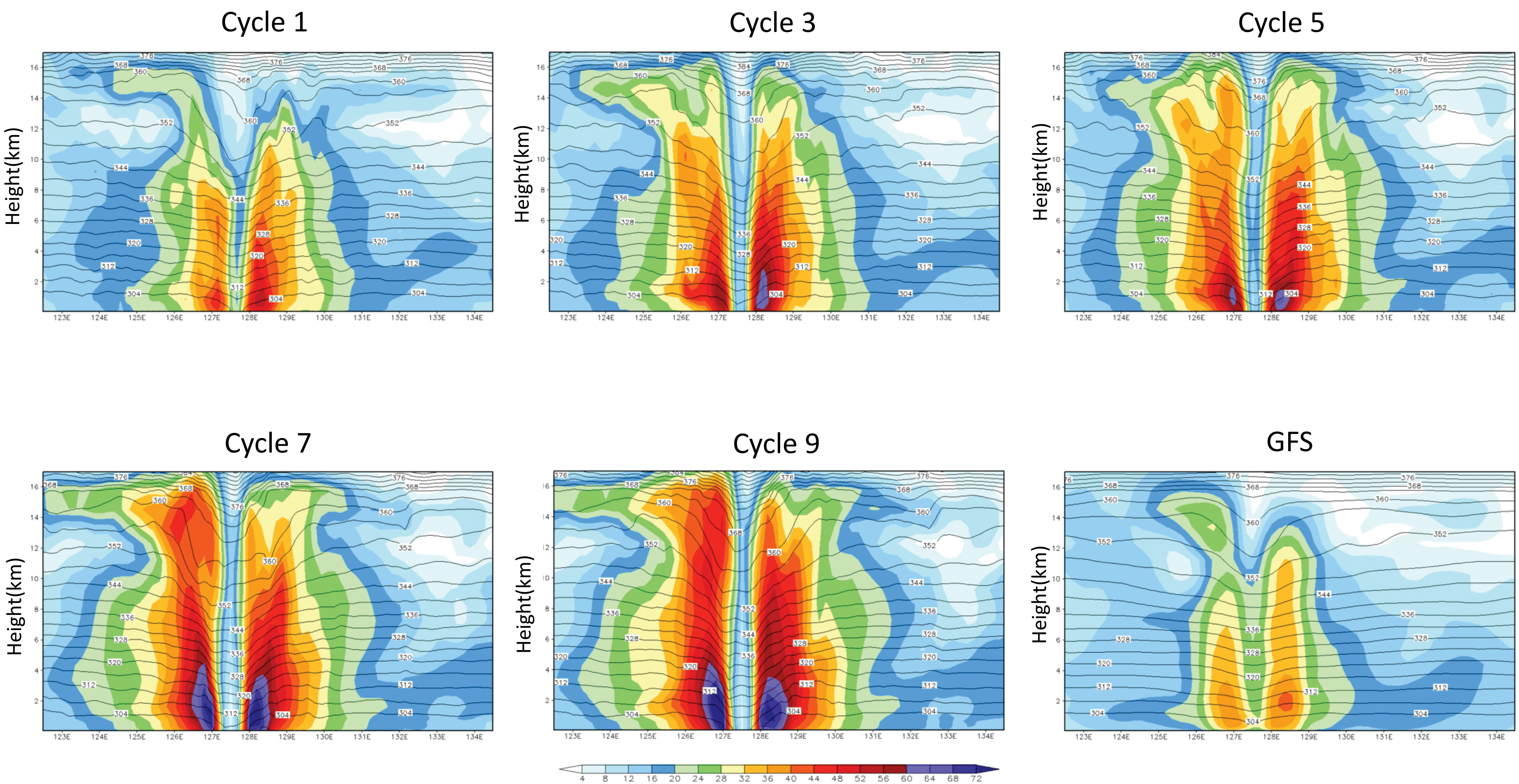
Dynamical Vortex Initialization (DVI)

Surface wind speed (m s^{-1})



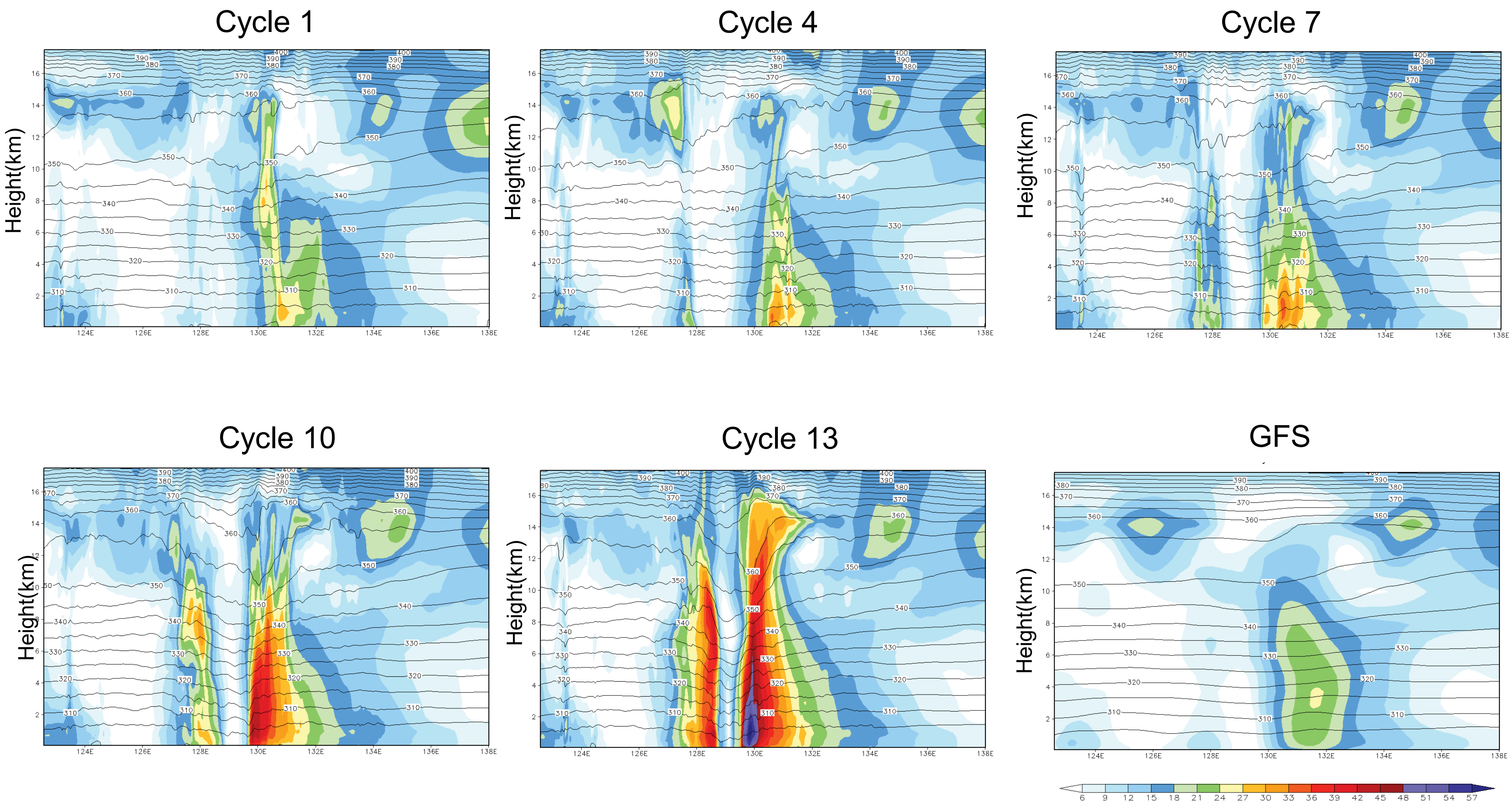
Dynamical Vortex Initialization (DVI)

Vertical-zonal cross-section through TC center



Wind speed (m s^{-1}, Shaded)
& Theta (K)

Vertical-zonal cross-section through the TC center



Wind speed (m s^{-1}, Shaded) & Theta (K)

Vortex Bogus for cases without deepening (Wang, 1998)

$$V = V^{env} + (V^{vortex} + V^{bogus})$$

V^{env} : *Environment part of WRF*

V^{vortex} : *vortex part of WRF*

V^{bogus} : *axisymmetric bogus vortex*

Empirical bogus vortex for horizontal wind components

$$V_T(r,p) = \begin{cases} V(r)\sin\left[\dfrac{\pi}{2}\left(\dfrac{p-p_t}{P_s-P_t}\right)\right], & p \ge 100mb \\ 0, & p < 100mb \end{cases}$$

V_T : *Tangential wind*

V_D : *Difference in* max. *wind between Obs. and WRF*

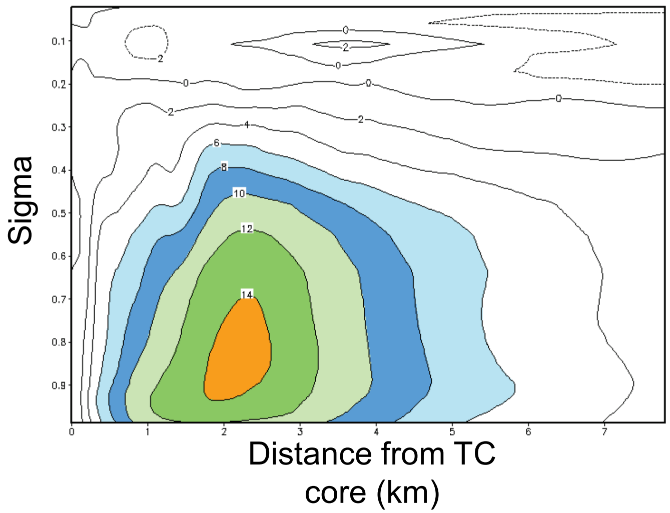
$$V(r) = \begin{cases} \dfrac{1}{2}V_D\left(\dfrac{r}{r_m}\right)\exp\left[1-\left(\dfrac{r}{r_m}\right)\right], & r \ge R_0 \\ 0, & r < R_0 \end{cases}$$

- **If the deepening does not occur after second cycle run, the empirical bogus method from Wang 1998) is applied.**
- **Only axisymmetric vortex parts for the 50% of the difference in maximum surface wind between WRF output and observation are added.**
- **Mass fields obtained by the nonlinear balance equation are also added.**

Vortex Bogus to ensure Deepening

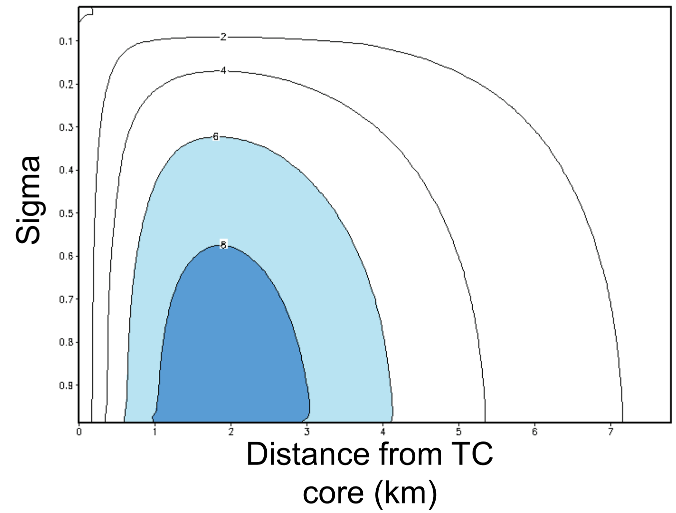
Azimuthal mean tangential wind

WRF (after cycle 2)

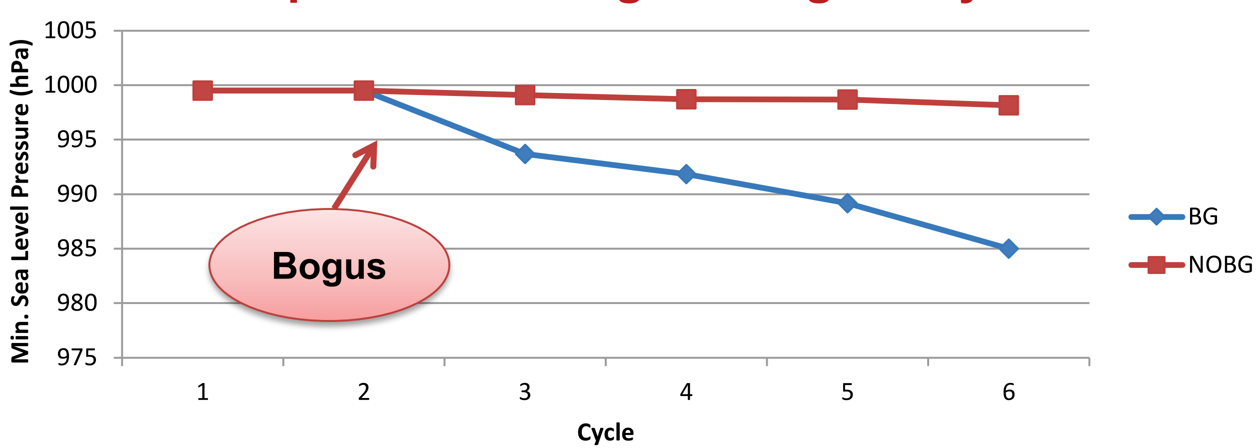


+

Bogus



Sea level pressure change during the cycle runs



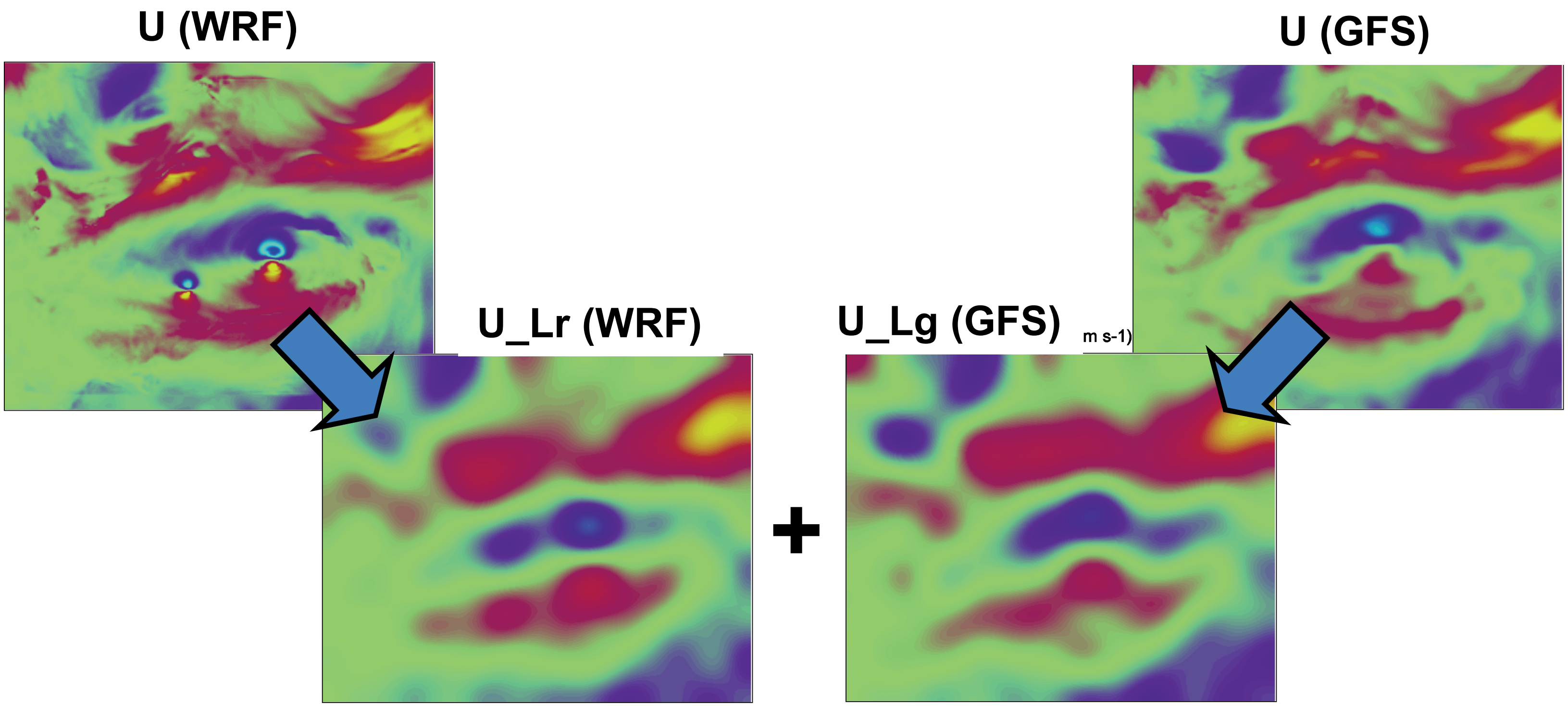
Large-Scale Spectral Nudging

Spectral Nudging (SN)

$$\frac{\partial u}{\partial t} = F(X) + \alpha\, w_\eta \left(u_{L_g} - u_{L_r}\right)$$

where

$$\begin{cases} u = \text{Nudged } u - wind \\ u_g = \text{Variable of Global Model} \\ u_r = \text{Variable of Regional Model} \\ u_{L_g} = \text{Large} - \text{Scale Variable of Global Model} \\ u_{L_r} = \text{Large} - \text{Scale Variable of Regional Model} \\ F(X) = \text{Model operator} \\ w_\eta = \text{Weighting Function} \\ \alpha = \text{Weighting } (0.0003) \end{cases}$$



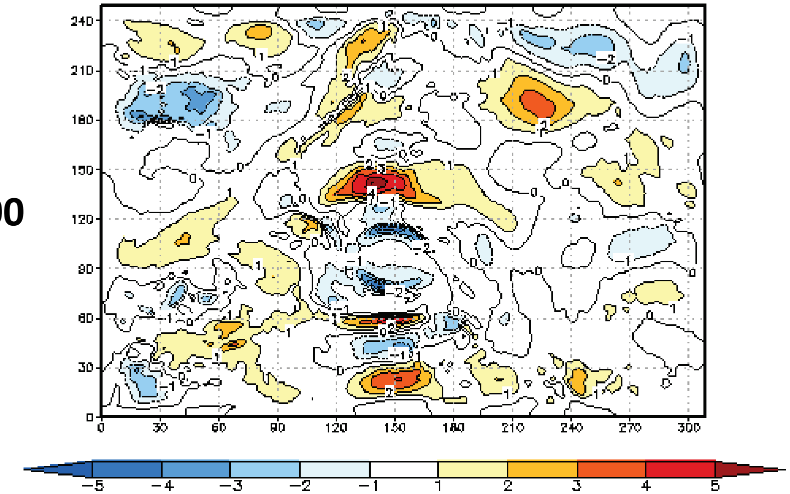
Spectral nudging is applied to horizontal wind and temperature

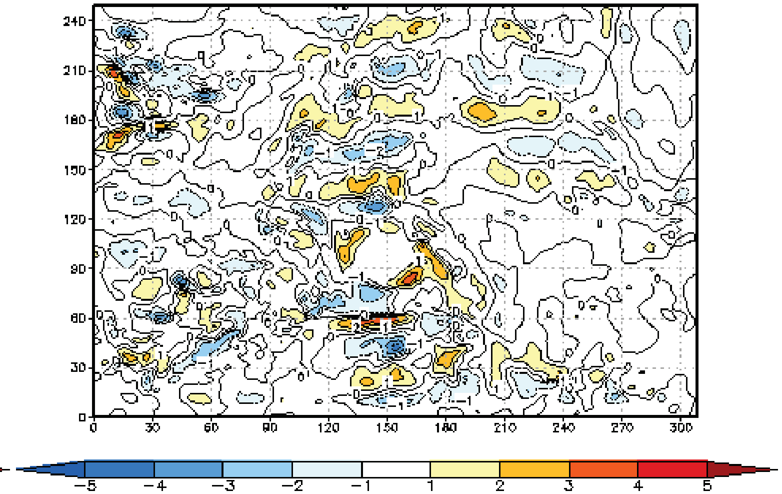
Large-Scale Spectral Nudging

Differences in environmental component at forecast initial time (t_0)

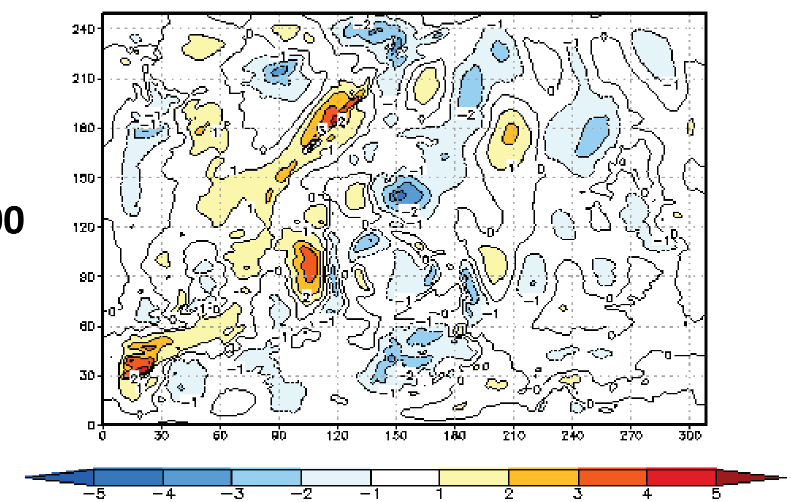
Without SN – Analysis | **With SN - Analysis**

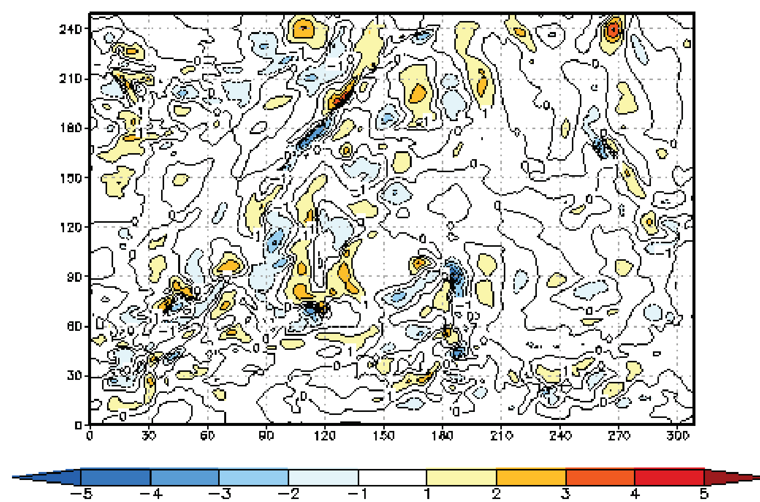
U500





V500





RMSE of large-scale fields (00 UTC 31 Sep 2010)

Variables	Without SN	With SN
SLP (hPa)	0.63	0.50
U850 (m s^{-1})	1.25	0.63
V850 (m s^{-1})	0.38	0.16
T850 (K)	1.06	0.39
U500 (m s^{-1})	1.11	0.60
V500 (m s^{-1})	0.97	0.28
T500 (K)	0.38	0.13

SN leads to less errors in large-scale fields.

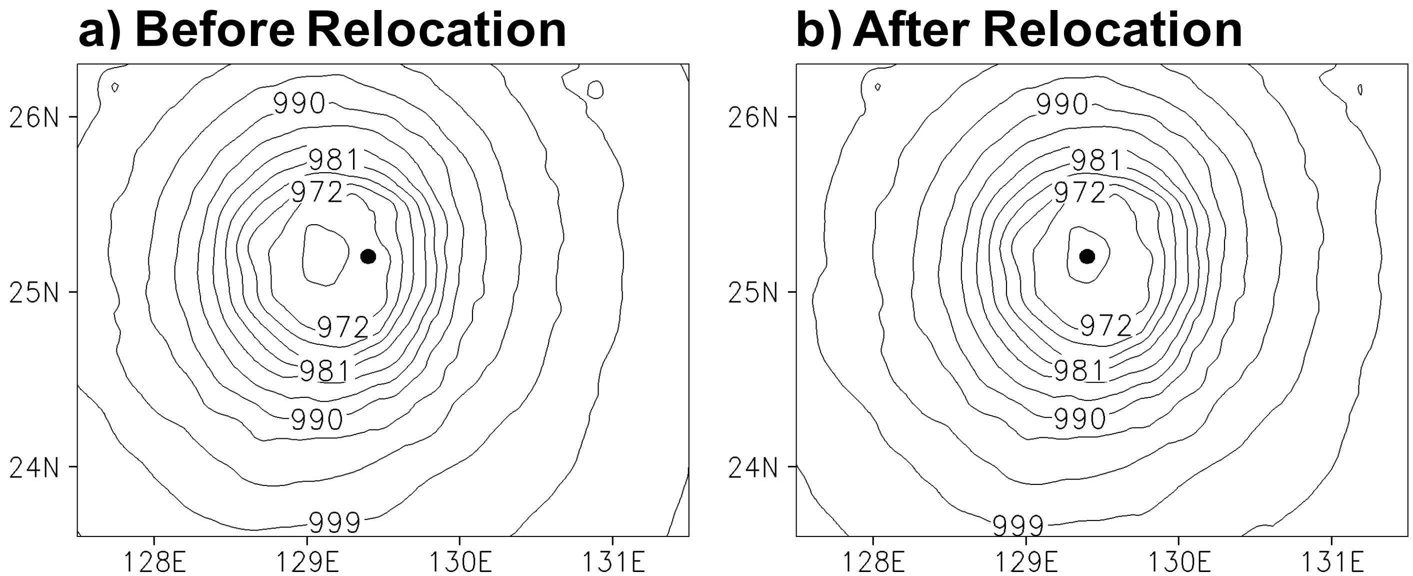
Relocation of TC vortex

$$V(x,y,z,t) = V^{env}(x,y,z,t) + V^{vortex}(x+dx, y+dy, z, t)$$

$$dx = x_1 - x_2 \qquad x_1, y_1 : observed\ \ center$$

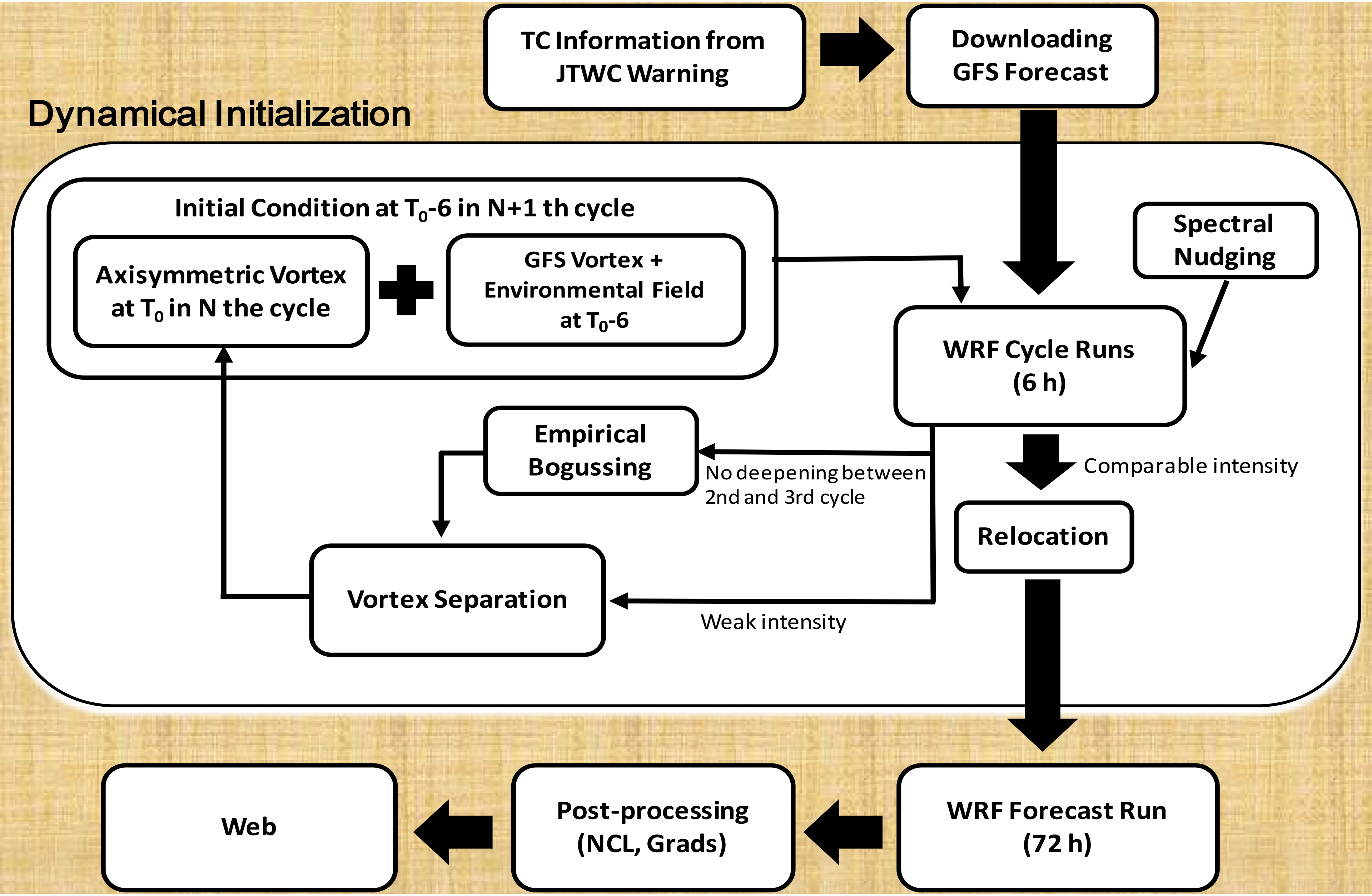
$$dy = y_1 - y_2 \qquad x_2, y_2 : simulated\ center$$

Surface Pressure (00 UTC 31 Sep 2010)

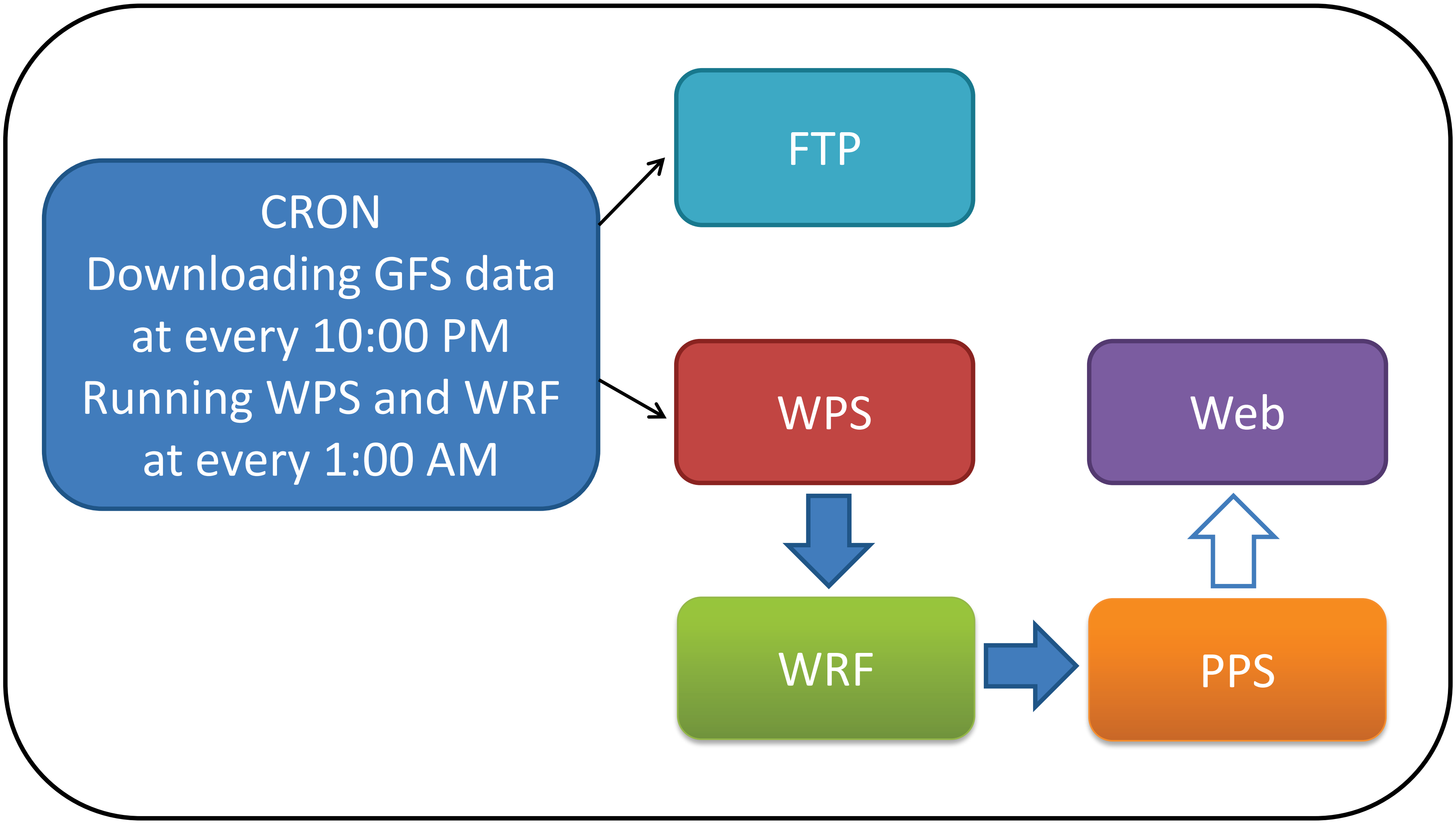


- To relocate the TC after the last cycle run.
- The vortex part of WRF output is separated from the environment using the filter method from Kurihara et al. (1993), and the vortex part is relocated to the observed TC center and is merged with the environmental component.

IPRC Real-time TC Forecasting System



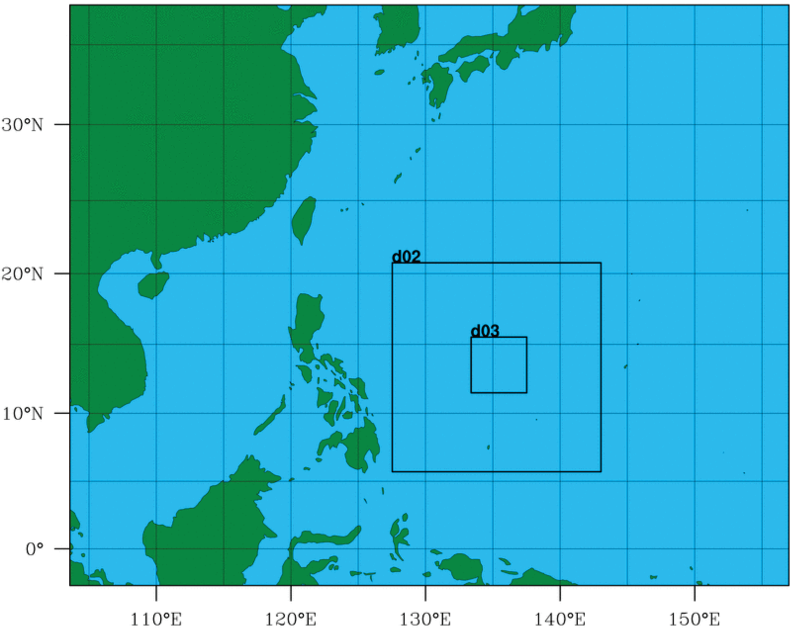
Automatic run of Real-time Forecasting System of TCs



Forecast Run

Model configuration

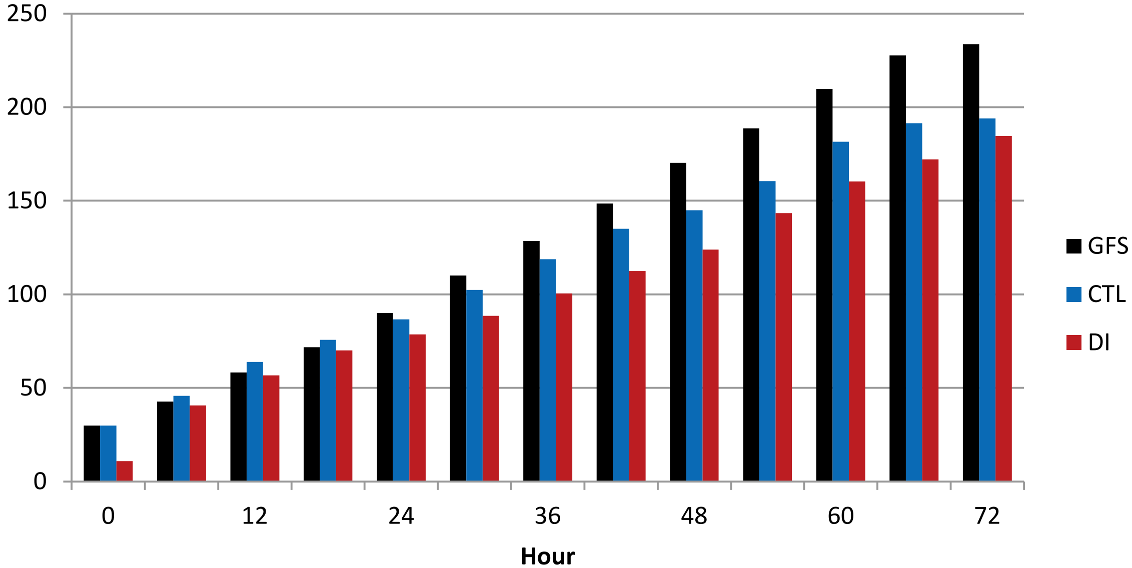
Domains



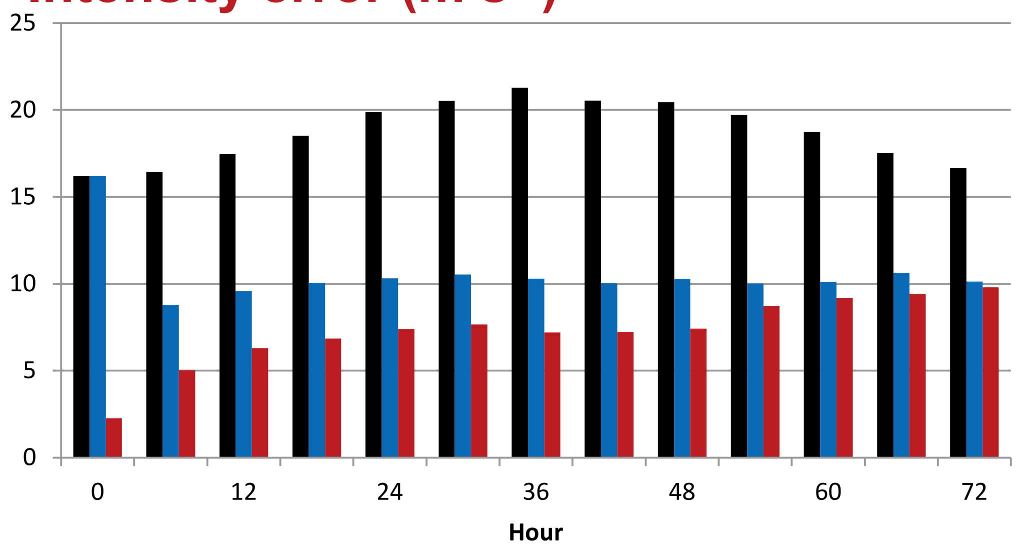
Model Configuration			
Model Prototype	WRFV3.3		
Horizontal grids (resolution)	DM1 311X251 (18km)	DM2 271X271 (6km)	DM3 211X211 (2km)
Vertical layers(P top)	28 levels (50hPa)	28 levels (50hPa)	28 levels (50hPa)
Time-step	90s	30s	10s
CPS	KF	None	None
PBL	YSU		
MP	WSM6		
Radiation	Dudhia / RRTM		
Surface	NOAH		
Moving nesting	NO	YES	YES
Forcings (Initial, Boundary)	3hourly NCEP GFS forecast data (0.5degree)		
Initial time	Every 00 UTC & 12 UTC, 15-20 Oct. 2010		
Simulation period	72hs		

Statistics averaged for 69 forecasts for 2010 and 2011

Position error (km)

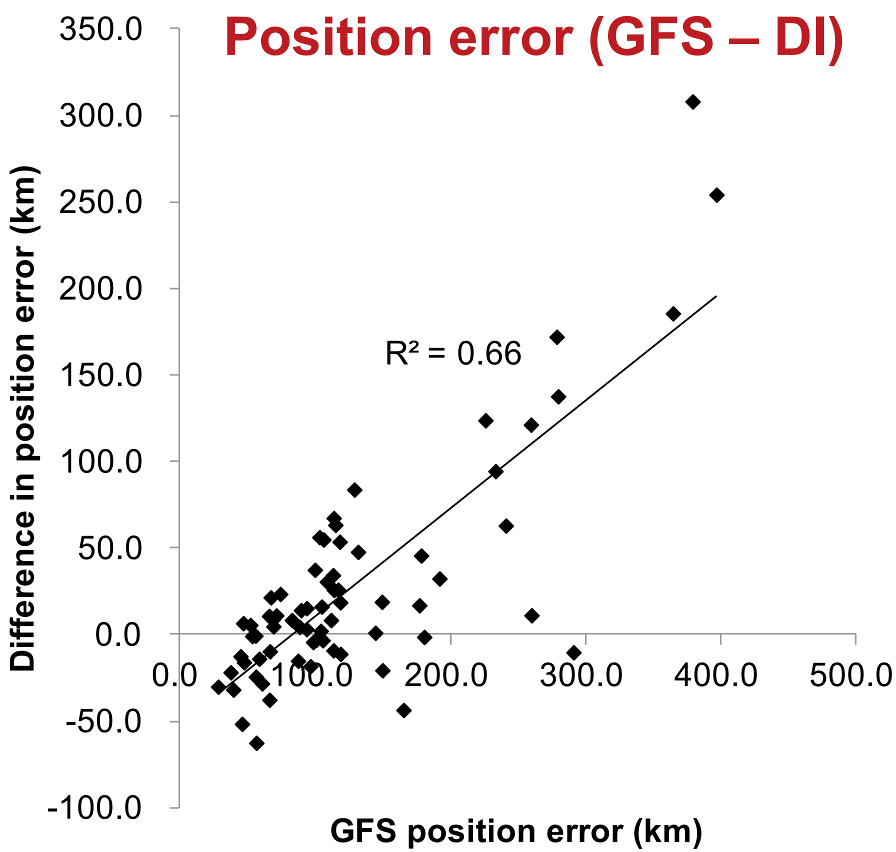


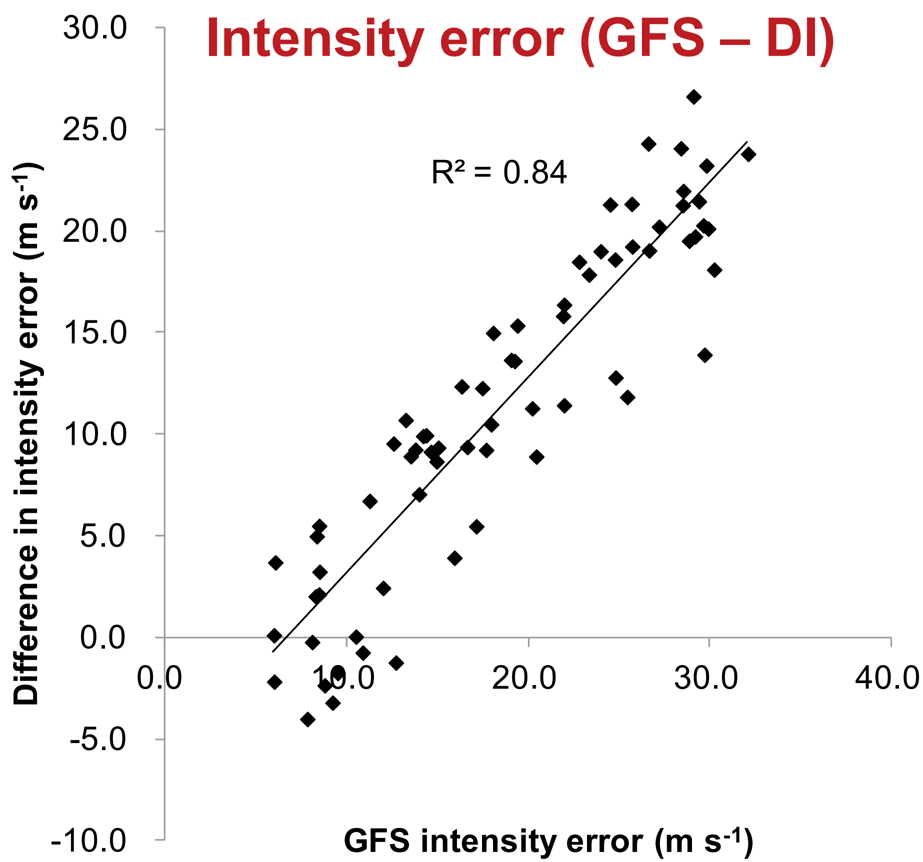
Intensity error (m s^{-1})



GFS	**Low-resolution GFS forecast**
CTL	**High-resolution WRF forecast without DI**
DI	**High-resolution WRF forecast with DI**

Error transferred from driving model





- The DI effect depends on the GFS forecast performance.
- The larger GFS forecast error, the more positive effect from DI

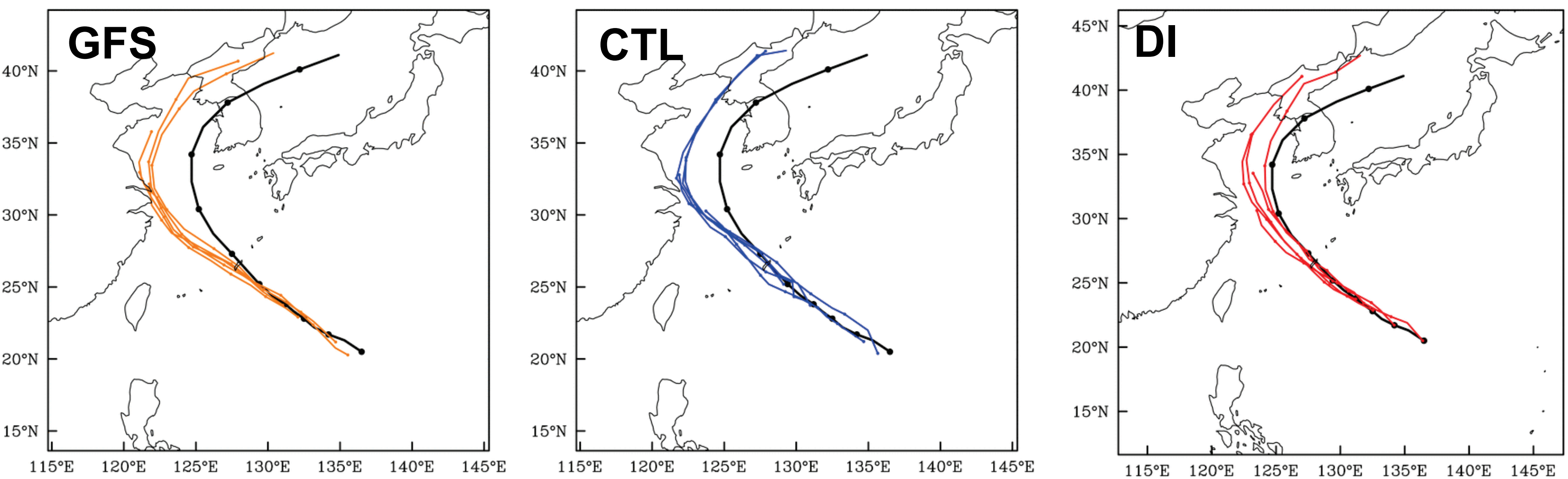
Case I: Typhoon Kompasu

Forecast initial times	forecasts
00 UTC 29 Aug 2010 ~ 00 UTC 31 Aug 2010	5

Statistics averaged for 5 forecasts

72h mean error	Position (km)	Intensity (m/s)
GFS	271.3	28.2
CTL	226.6	18.4
DI	158.6	5.9

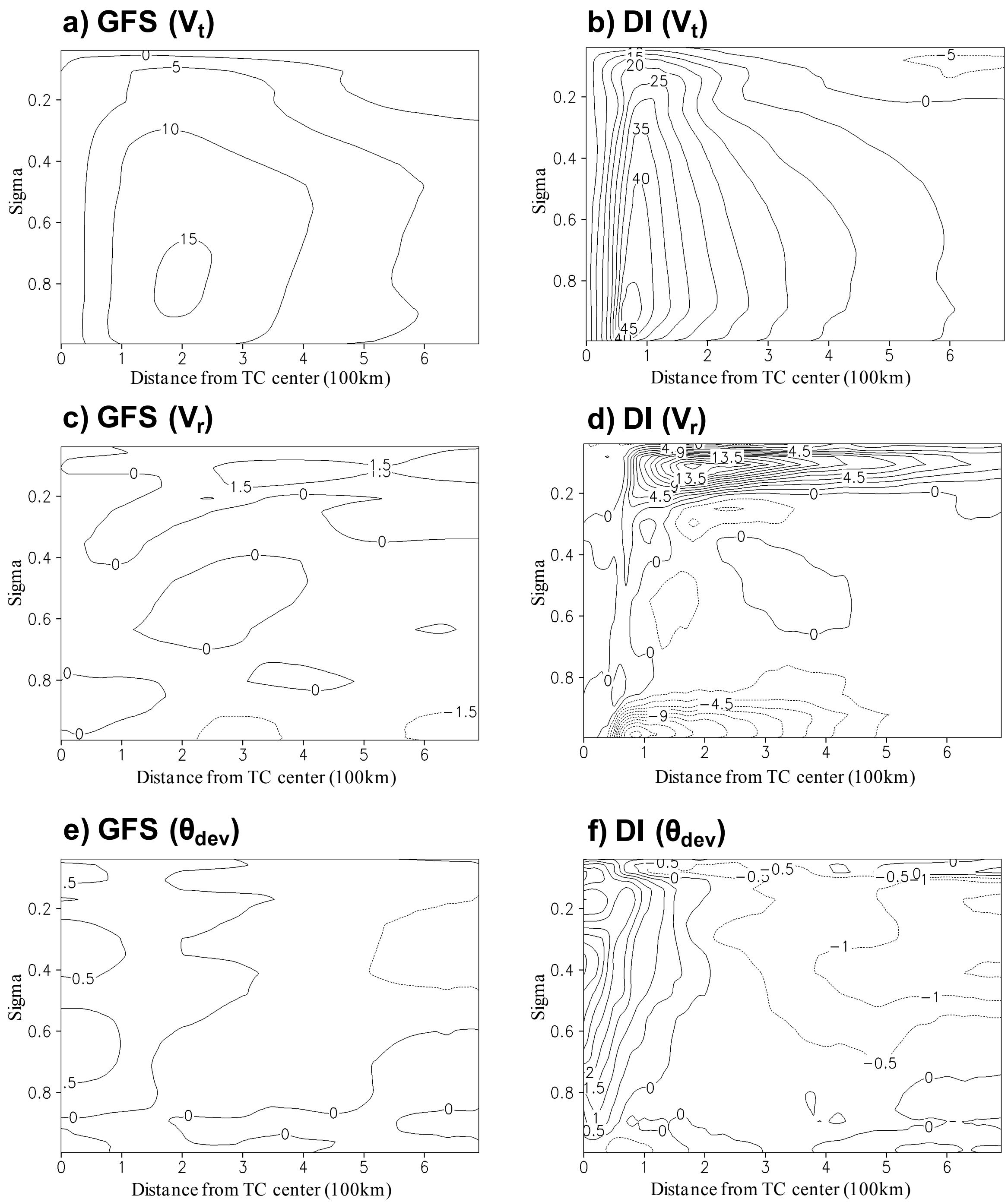
Tracks



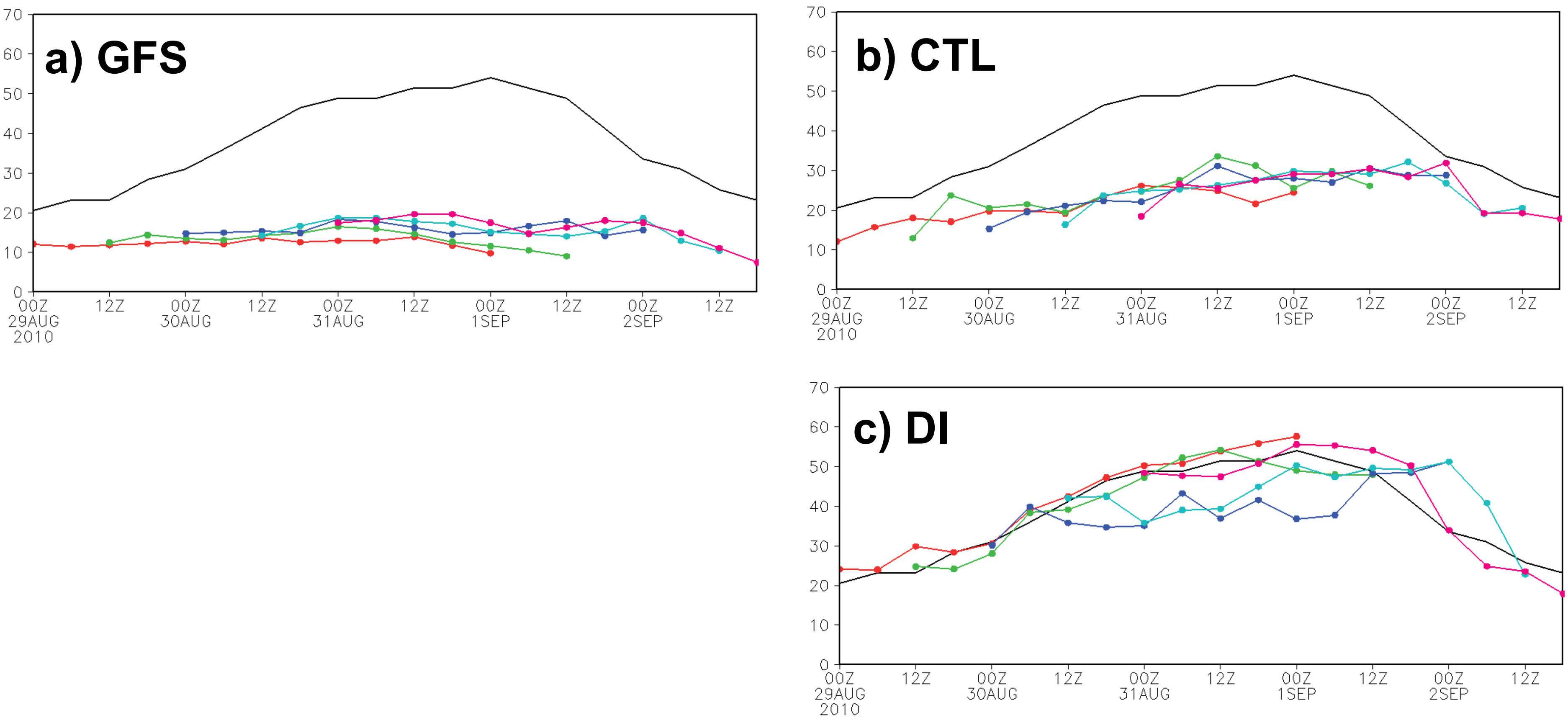
*Black line: JTWC best-track data

Initial Typhoon Kompasu

Initial time is 00 UTC 31 Aug.

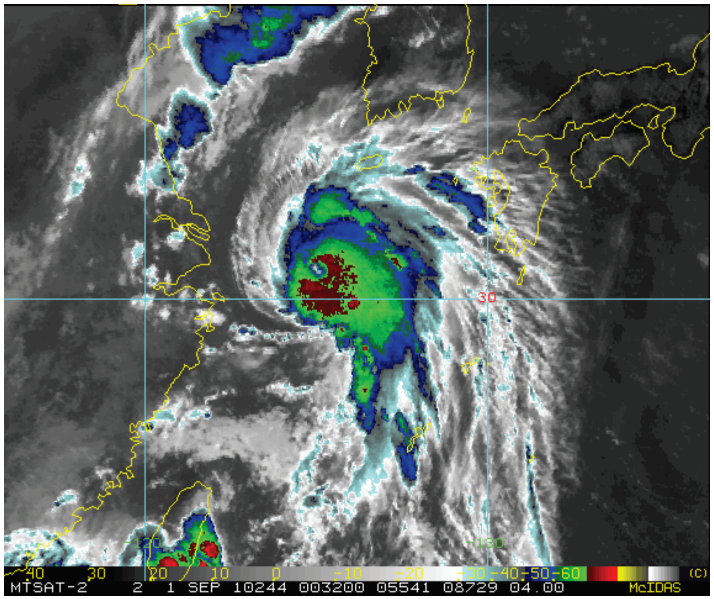


Max. surface wind speed ($m\ s^{-1}$) for Typhoon Kompasu

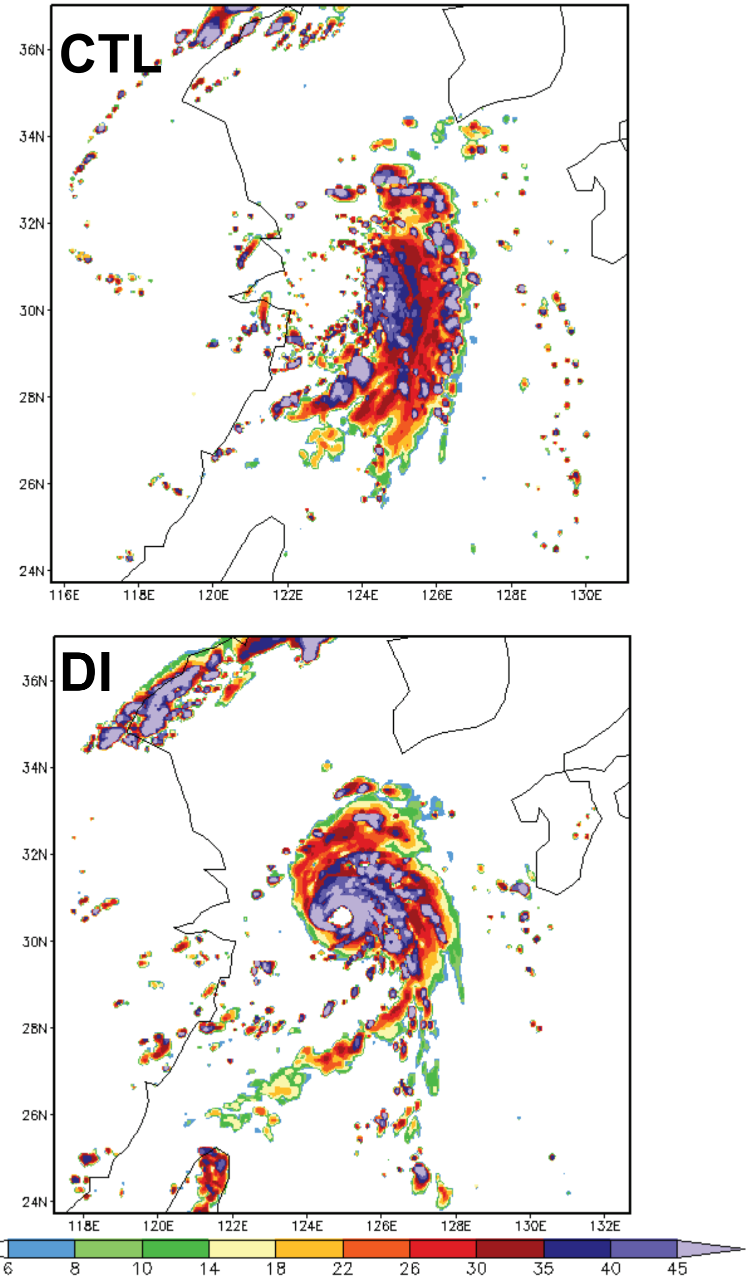


Horizontal structure of TC at peak intensity (00 UTC 01 Sep.)

Enhanced IR image



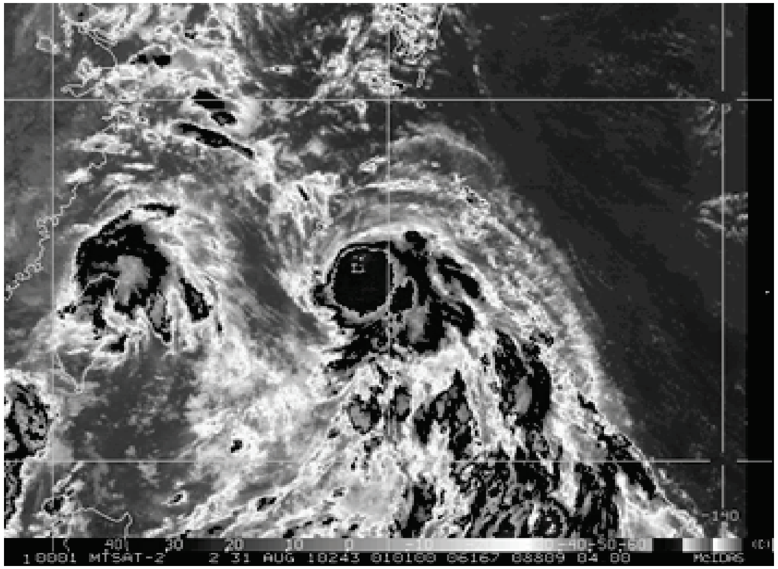
Radar reflectivity (dBZ)



Typhoon Kompasu

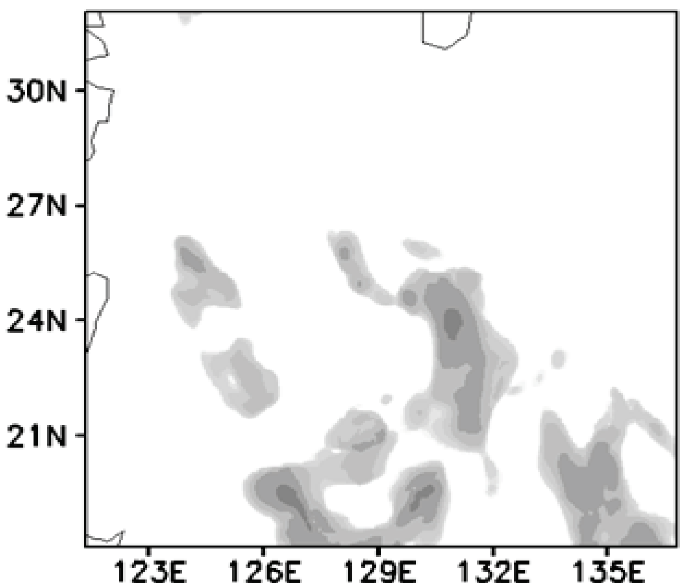
Forecast initial time is 00 UTC 31 Aug.

a) Enhanced IR Image

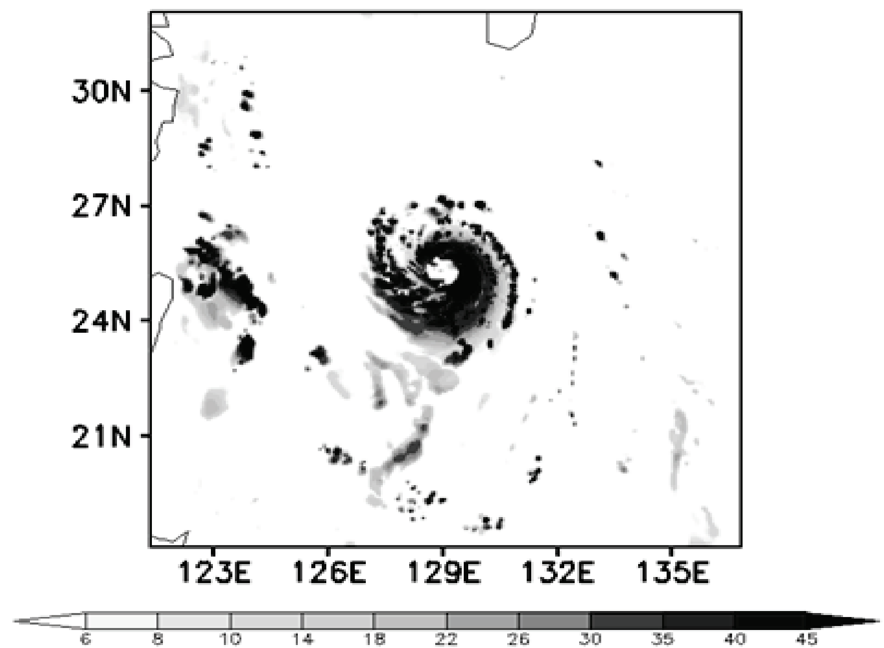


One hour prediction

b) CTL



c) DI



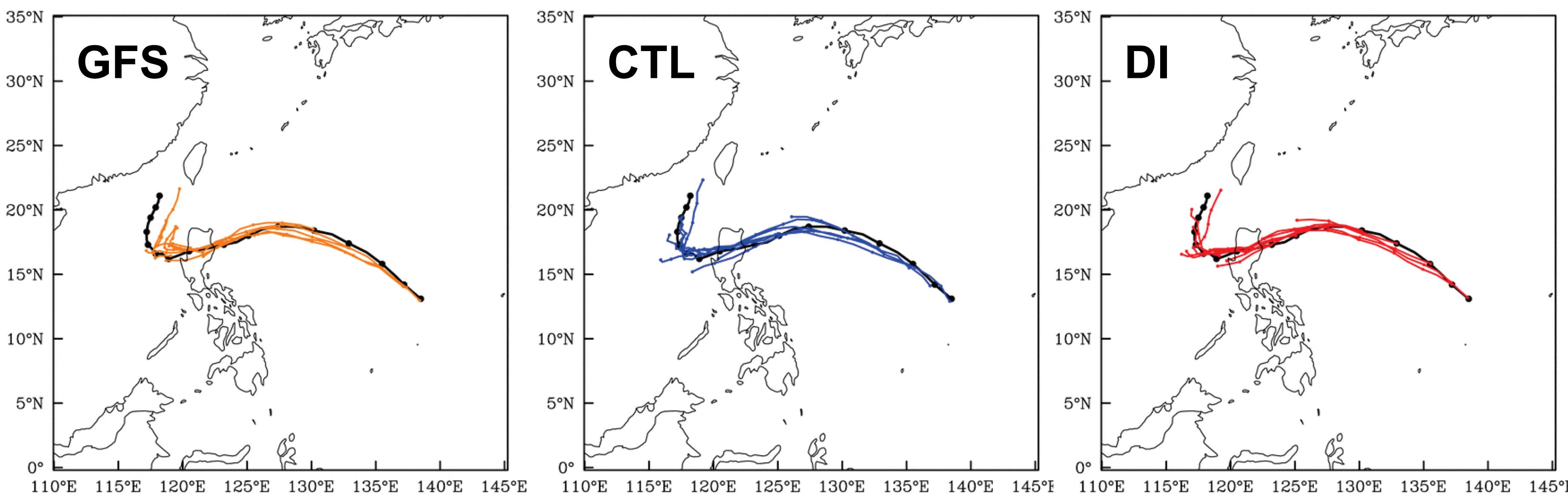
Case II: Typhoon Megi (2010)

Forecast initial times	forecasts
1200 UTC 14 Oct 2010 ~ 0000 UTC 19 Oct 2010	10

Statistics averaged for 10 forecasts

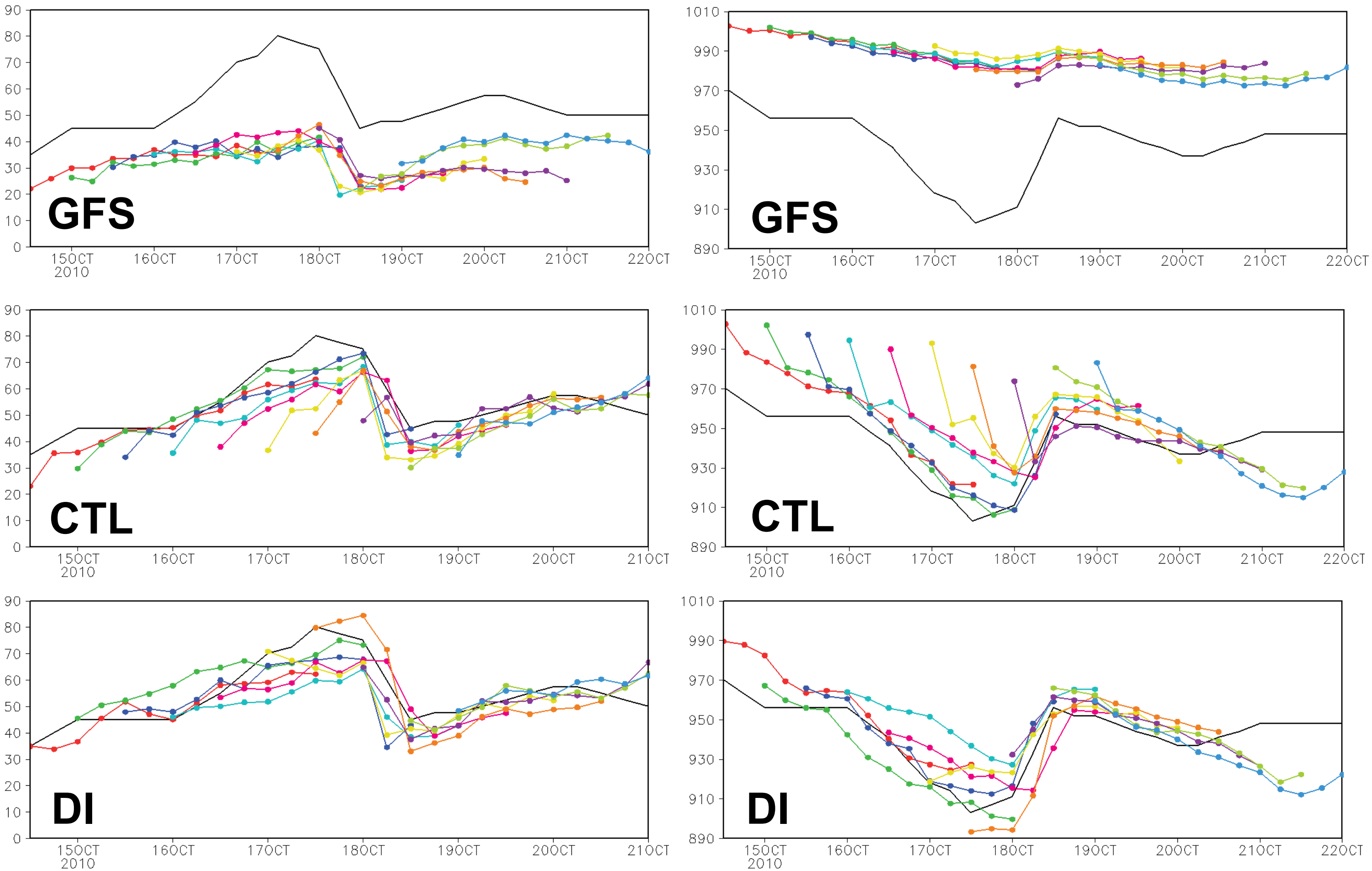
72h mean error	Position (km)	Intensity (m/s)
GFS	80.9	25.4
CTL	68.2	9.6
DI	58.1	7.6

Track



*Black line: JTWC best-track data

Max. surface wind speed (m s^{-1})   Min. sea level pressure (hPa)

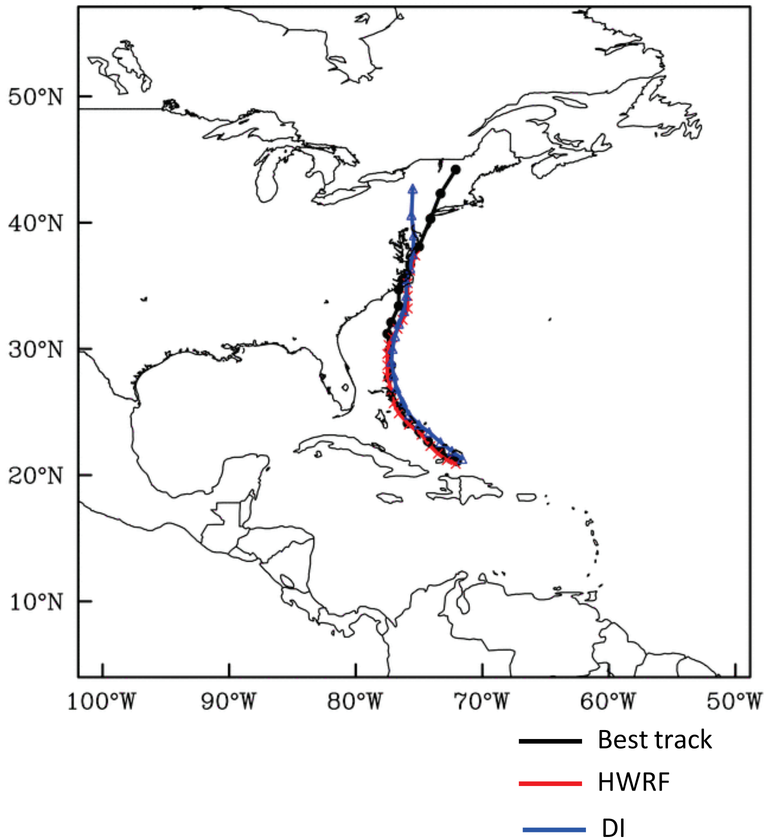


HWRF Model Configuration

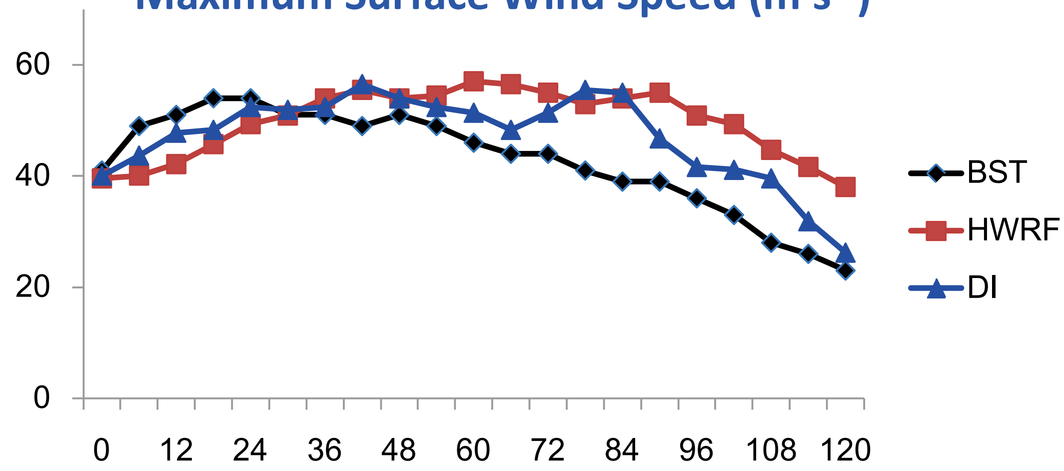
Model Prototype	WRF NMM	
Horizontal grids (resolution)	DM1 432X216 (27km)	DM2 100X60 (9km)
Vertical layers(P top)	43 levels (50hPa)	43 levels (50hPa)
Time-step	54s	18s
CPS	SAS	
PBL	NCEP GFS	
MP	Tropical Ferrier	
Radiation	GFDL	
Surface	GFDL slab model	
Moving nesting	NO	YES
Forcings (Initial, Boundary)	6-hourly NCEP GFS forecast data (1 degree)	

Case I: Hurricane IRENE (Initial forecast time: 00UTC 24 Aug 2011)

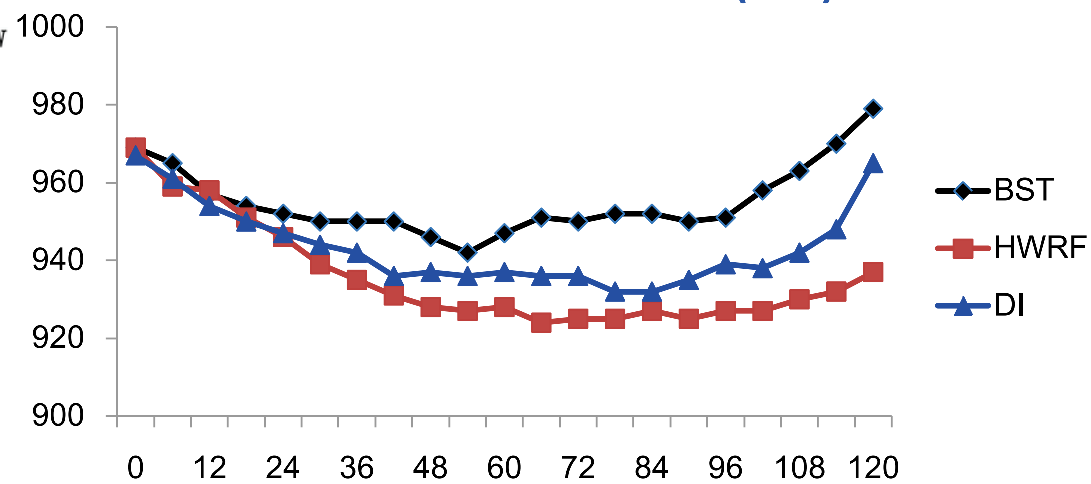
Track



Maximum Surface Wind Speed (m s^{-1})

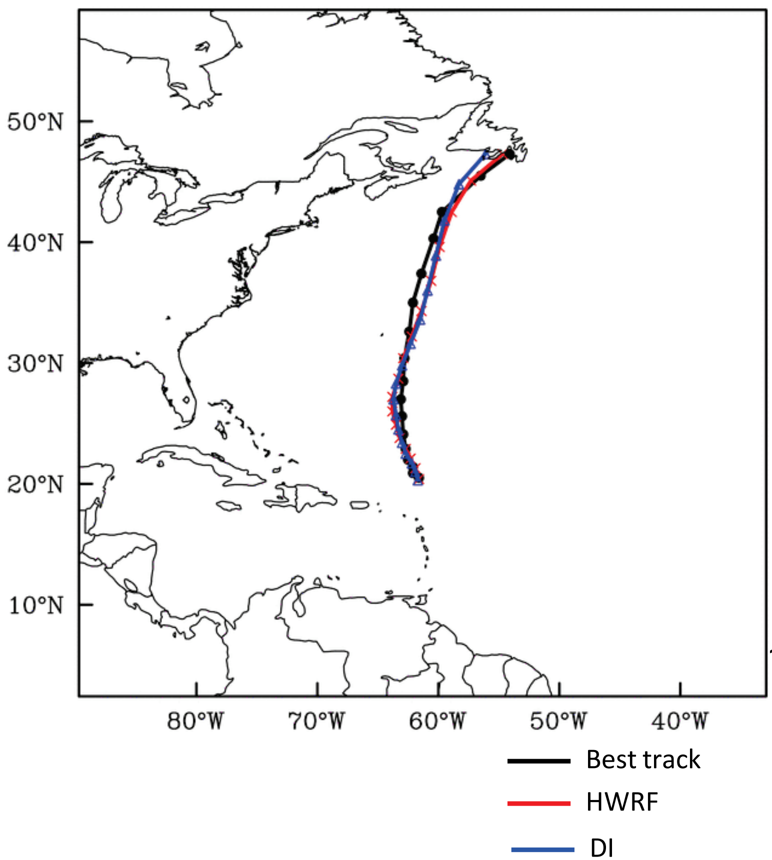


Minimum Central Pressure (hPa)

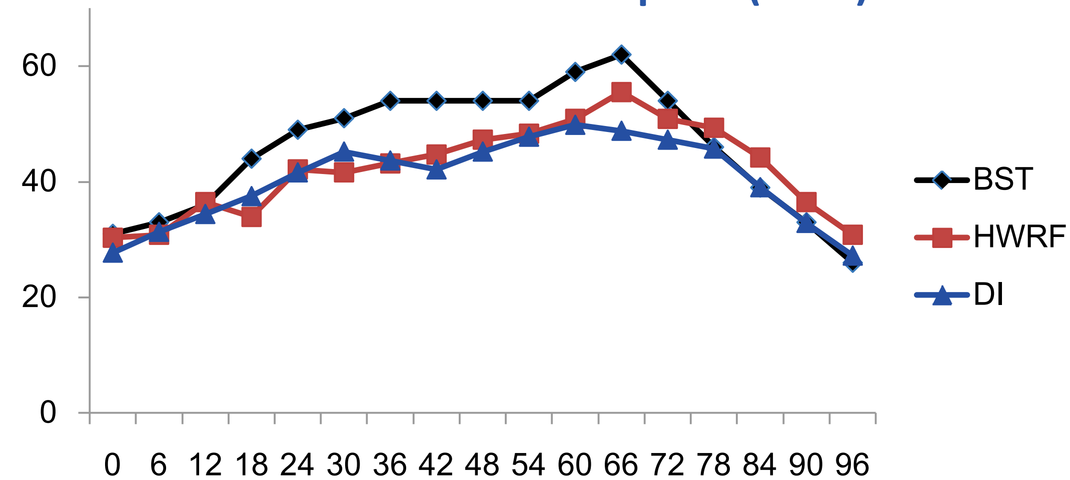


Case II: Hurricane OPHELIA (Initial forecast time: 12UTC 29 Sep 2011)

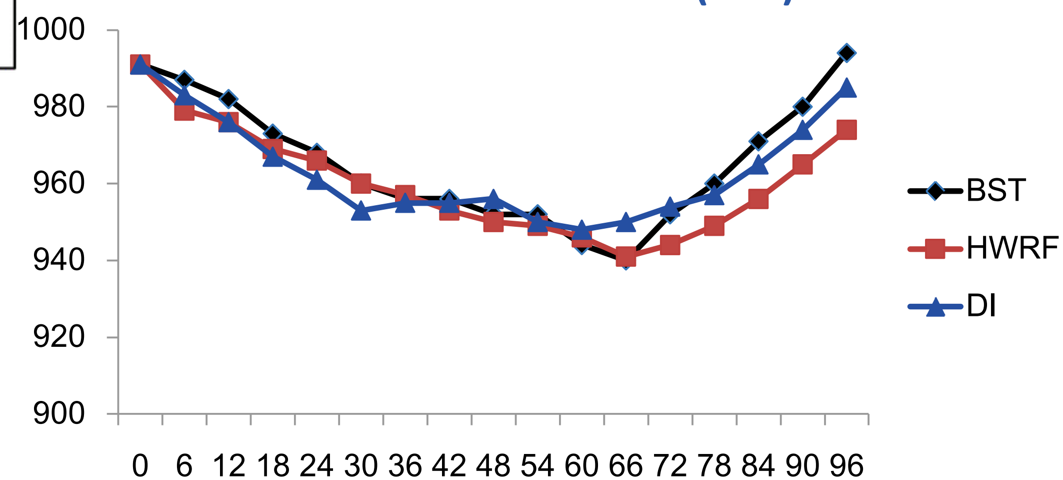
Track



Maximum Surface Wind Speed (m s^{-1})

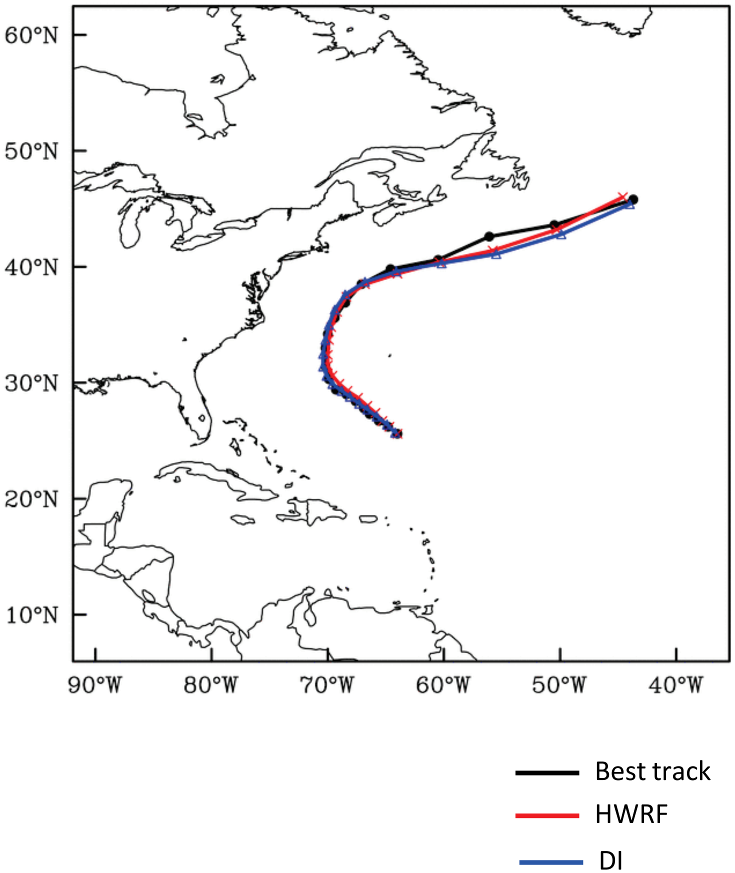


Minimum Central Pressure (hPa)

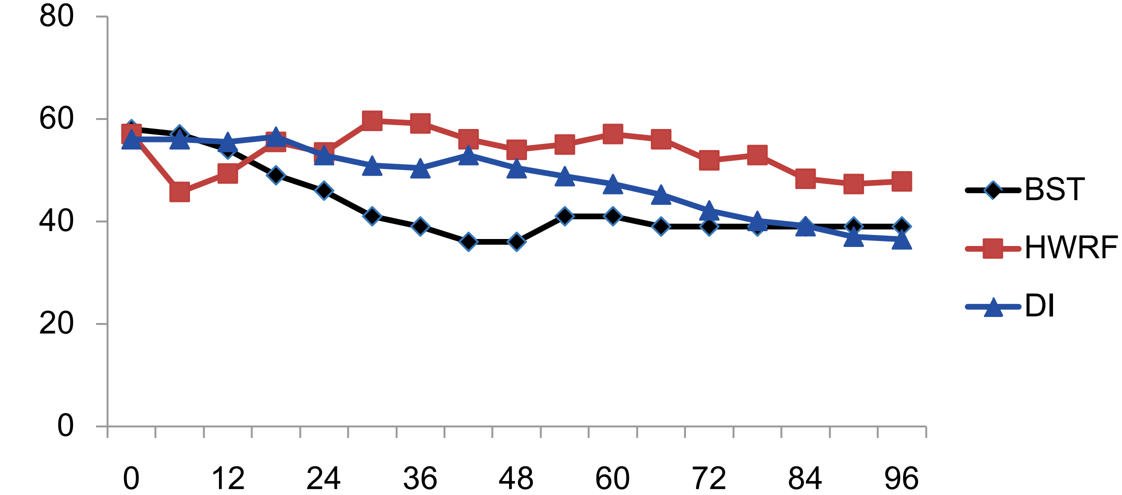


Case III: Hurricane KATIA (Initial forecast time: 00UTC 06 Sep 2011)

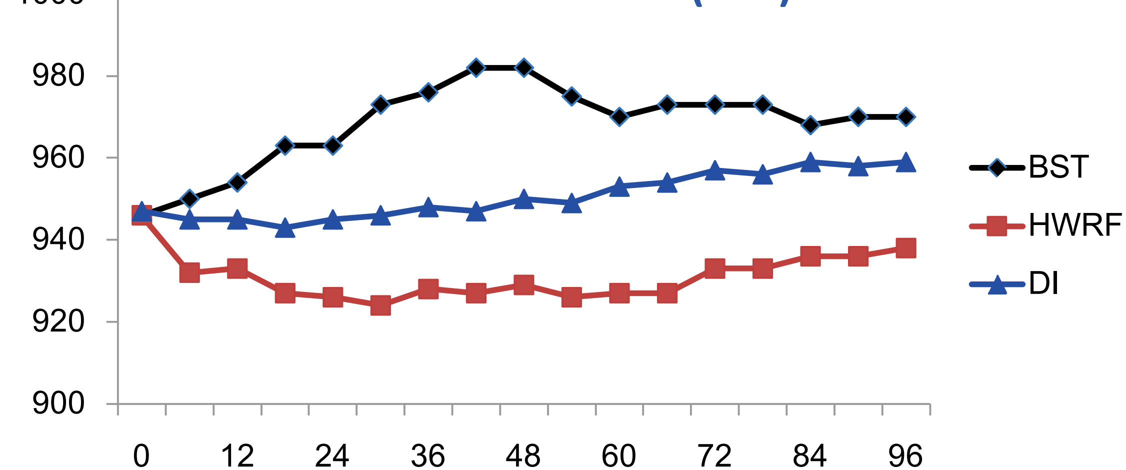
Track



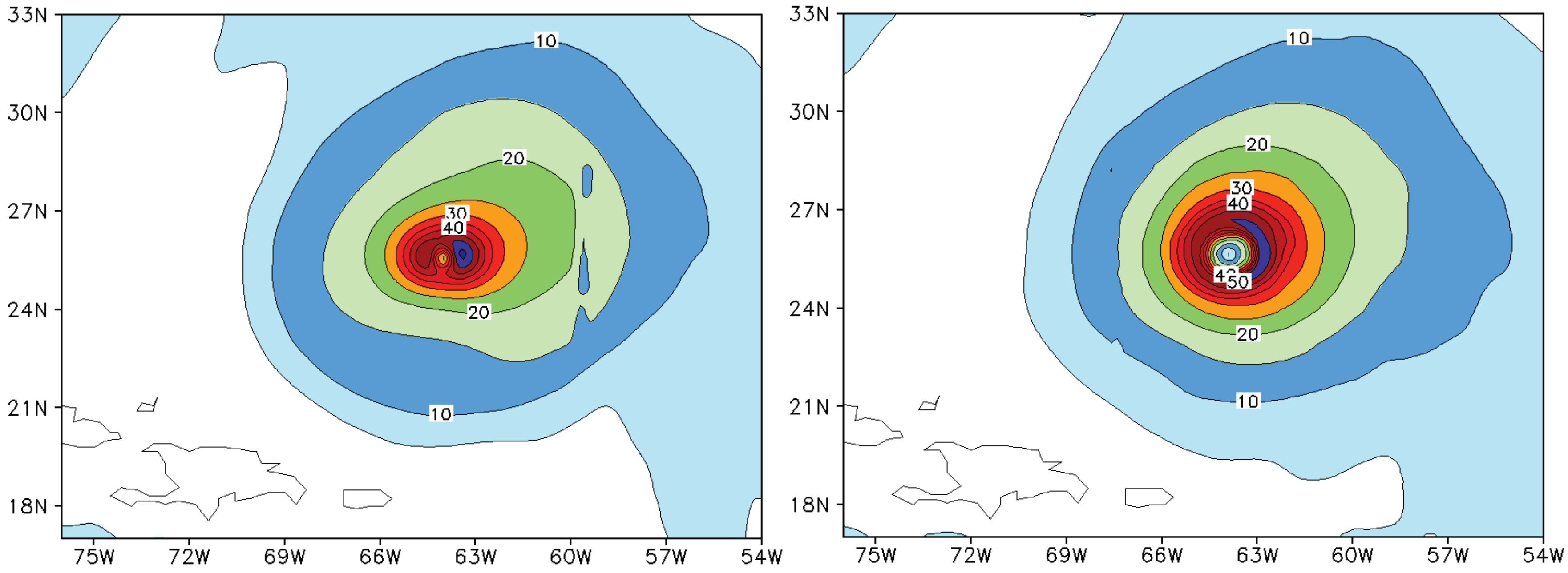
Maximum Surface Wind Speed (m s^{-1})



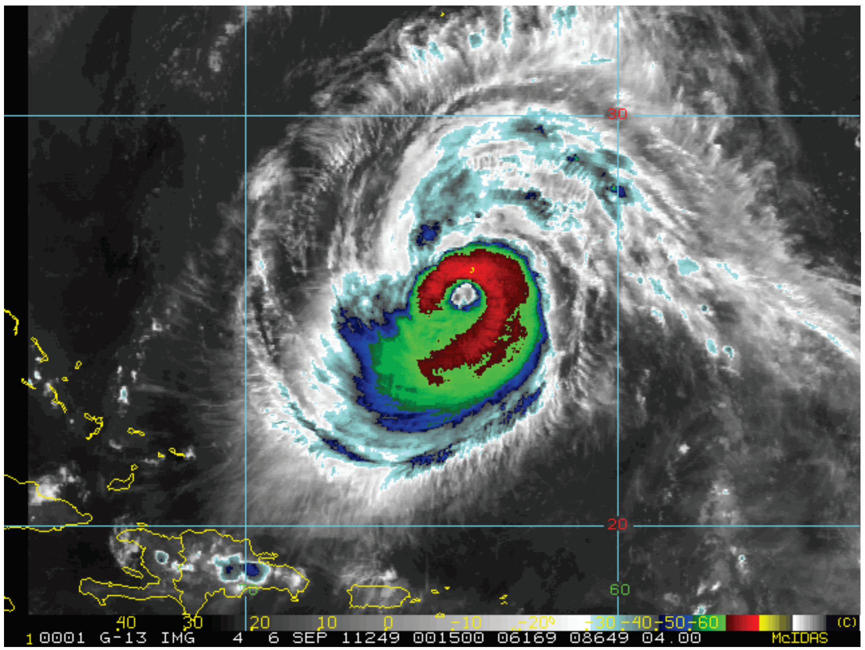
Minimum Central Pressure (hPa)



Surface Wind Speed (00 UTC 06 Sep 2011, KATIA)

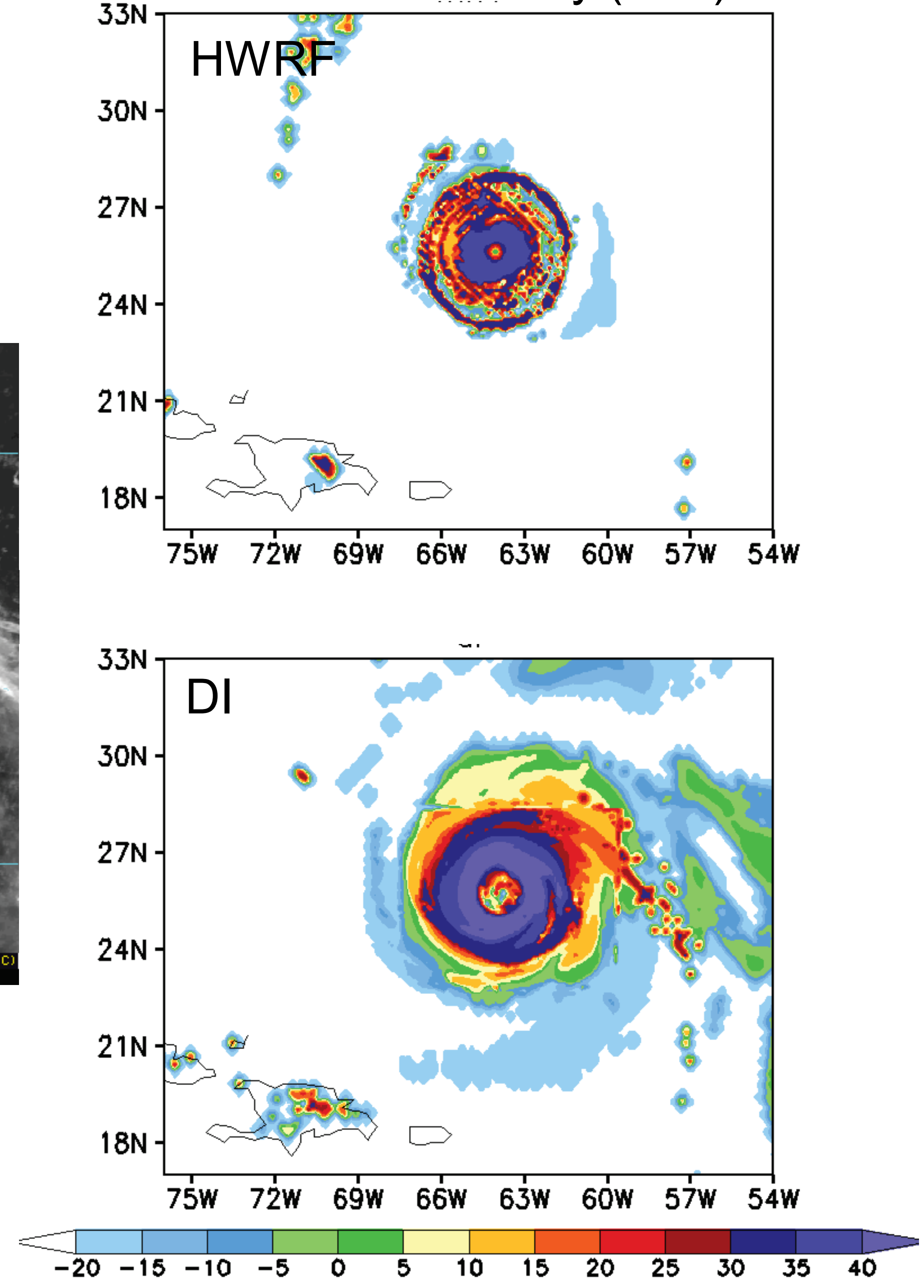


Satellite Enhanced Image (KATIA)
(0015 UTC 06 Sep 2011)



*15 min after forecast initial time

Radar Reflectivity (dBZ)



Summary

- A DVI scheme was developed and implemented into the a real-time forecast system for Northwest Pacific of TCs using the WRF model;
- The DVI scheme spins up both the axisymmetric and asymmetric vortex components from 6-h cycle runs with SN to reduce errors in large-scale fields, achieving warm model startup;
- The TC vortex created with the new DVI is well adapted to the large-scale environment the TC is embedded, such as the asymmetric structure forced by storm motion and vertical wind shear.
- The new scheme can improve not only the TC intensity but also the TC structure and features the warm start-up of model physics;
- The IPRC real-time TC forecasting system with this DVI scheme has been run real-time since 2012 TC season;
- The scheme has been implemented and tested in HWRF as well.

Website: http://iprc.soest.hawaii.edu/users/chunxi

Future Development

- To reduce the cycle runs by improving the initial TC vortex in the global analysis at t_0-6 using the 3D variational data assimilation (3DVAR) scheme GSI in the HWRF model (to implement a large-scale SN scheme into the HWRF model for the cycle runs);
- To include a four-dimensional data assimilation (FDDA) scheme as used in the WRF-ARW model to weakly nudge the observed TC central SLP and other available data in the cycle run window to spin up the solution convergence, making the DVI more efficient;
- To perform at least one cycle run to achieve warm model startup by adjusting the TC intensity of the last cycle run by smooth/desmooth.
- To improve the calculation of the azimuthal mean vortex in height coordinate and interpolate the result back to the model levels in regions with significant topography.

Thank you

Questions/comments