Predictability and Observability of the Genesis of Tropical Cyclones through Cloud-resolving Ensemble Analysis and Forecasting

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Plans and Goals at PSU

Modeling: Real-time cloud-resolving ensemble analysis and forecasting assimilating airborne Doppler and dropsonde observations

Observations: Tracking the change of dynamics and thermodynamics as well as the surface fluxes associated with VHTs and VHT clusters

Science 1: The role of multiscale vortex interaction, upscale growth of diabatically generated vorticity anomalies in the genesis of tropical cyclones:

easterly waves ←→ "pouch" ←→ VHT clusters ←→ VHTs

Science 2: Observability of tropical cyclone genesis processes; flow and regime dependent tropical cyclone predictability

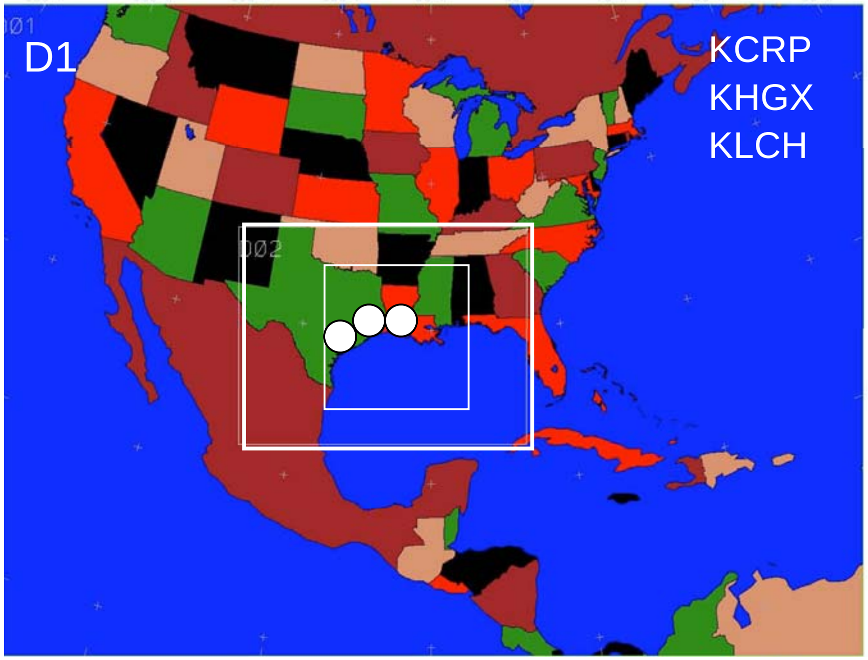
Assimilate W88D Vr for Humberto with EnKF

(Zhang et al. 2009 MWR)

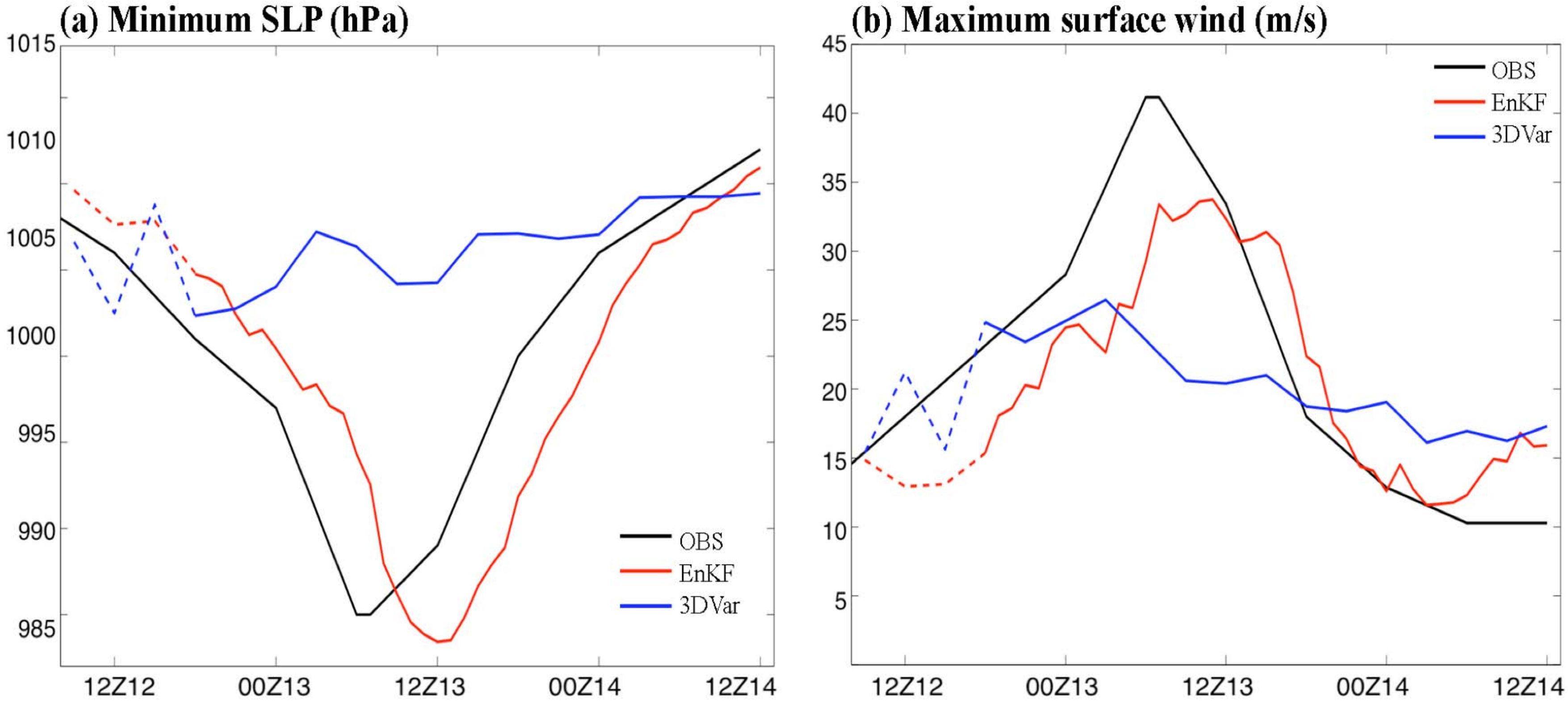
- WRF domains: D1-D2-D3 grid sizes---40.5km, 13.5km, 4.5km
- and EnKF (Hammil Whitaker 2002; Snyder and Zhang 2003)

  - WRF-EnKF (Meng and Zhang 2008a,b MWR); 30-member ensemble
  - Initialized at 00Z 12 using 3DVar background uncertainty with FNL analysis
  - Covariance localization (Gaspairi and Cohn 1999)
  - Covariance relaxation (Zhang et al. 2004)

- Data assimilated:
  - WSR88D at KCRP, KHGX and KLCH radar radial velocity every hour from 09Z to 21Z Sept 12, 2007
  - Data assimilation are performed for all domains; obs err 3m/s
  - Successive covariance localization: Radii of Infleunce=1800, 600 and 200km for 1/9, 1/3 and 5/9 of SOs, respectively



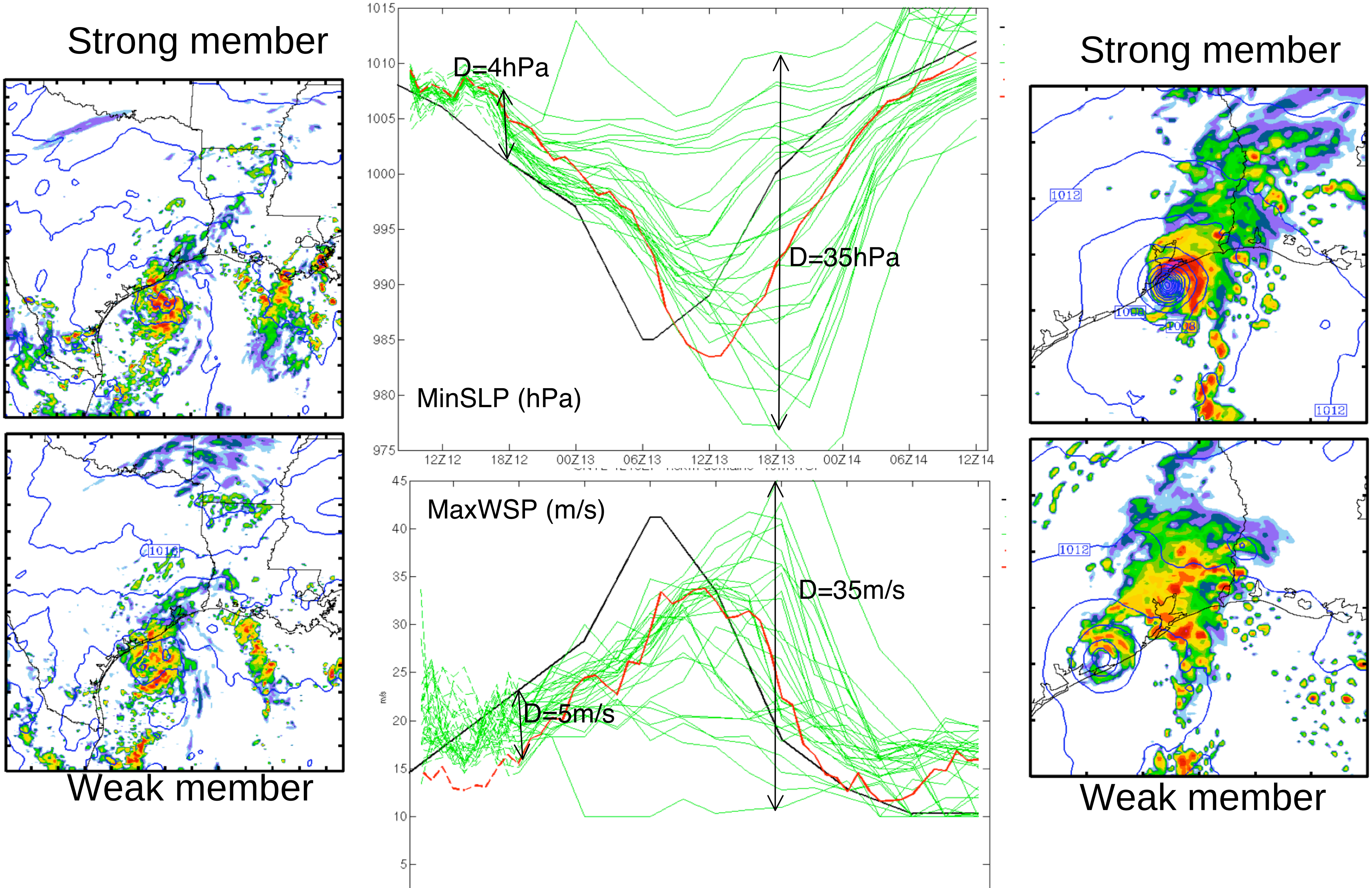
WRF/EnKF Forecast vs. Observations vs. 3DVAR



The WRF/3DVAR (as a surrogate of operational algorithm) assimilates the same radar data but without flow-dependent background error covariance, its forecast failed to develop the storm despite fit to the best-track observation better initially

(Zhang et al. 2009

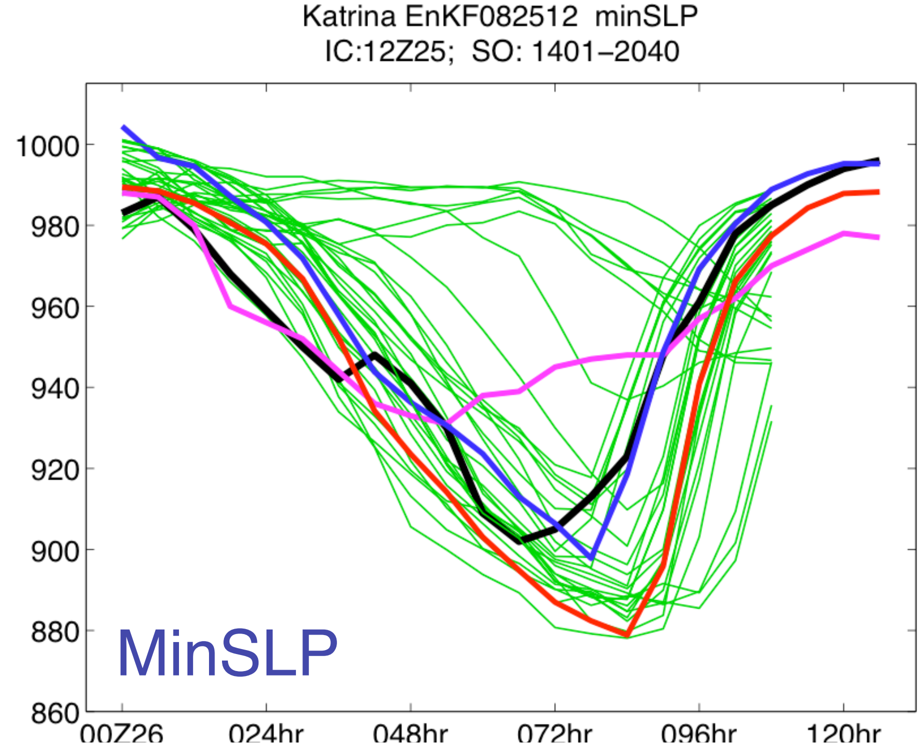
Ensemble Forecast and Predictability of Intensity

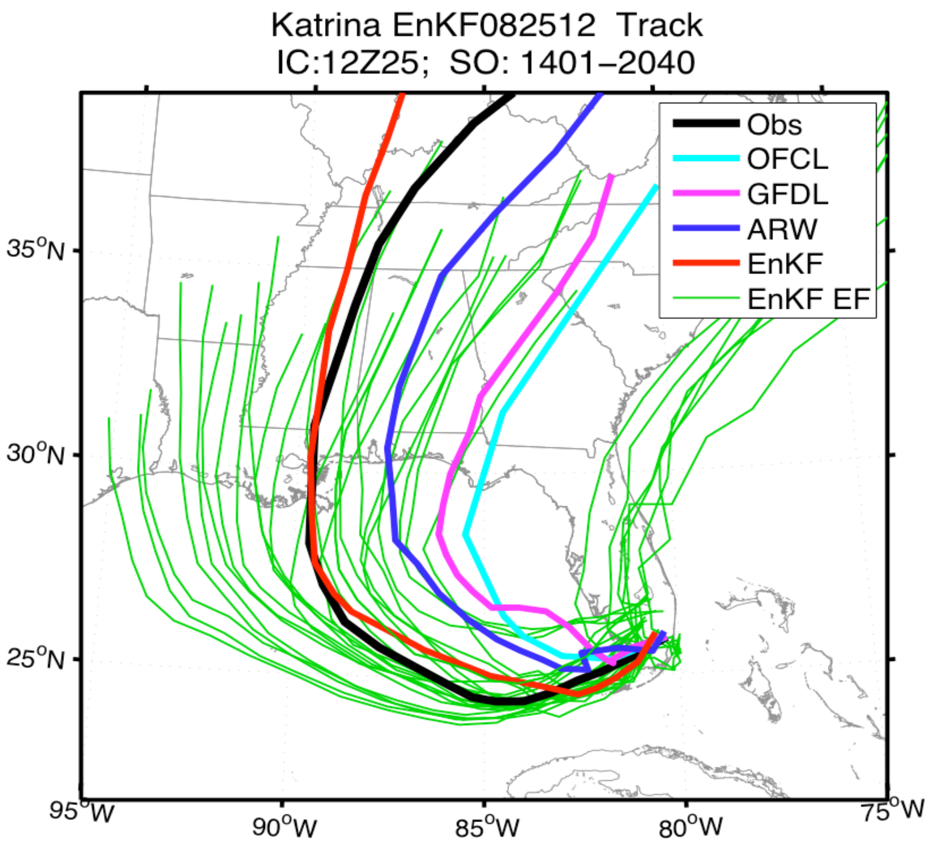


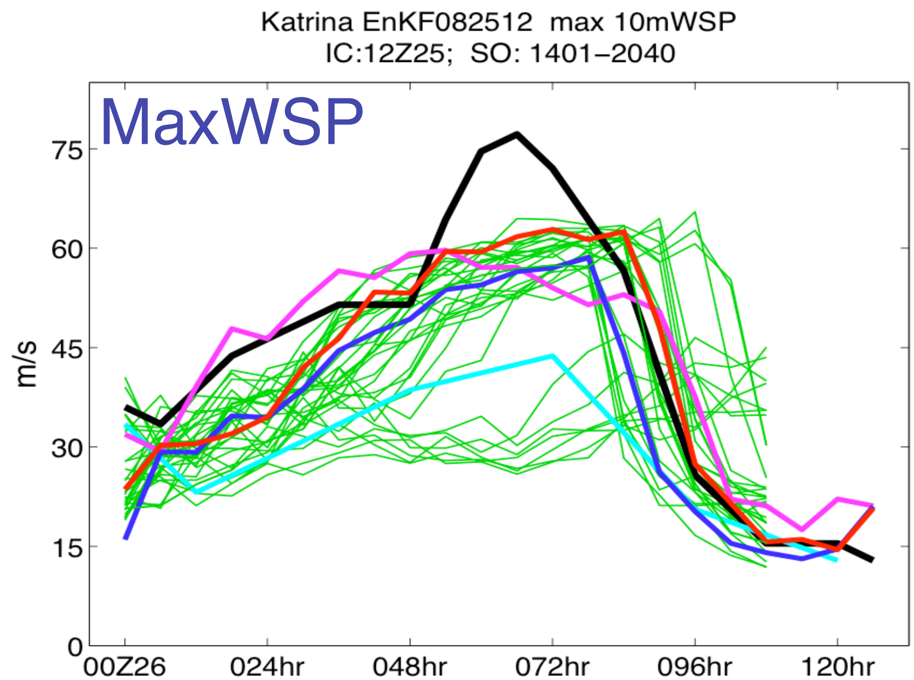
(Sippel and Zhang 2009a)

WRF/EnKF Performance (before Florida Landfall)

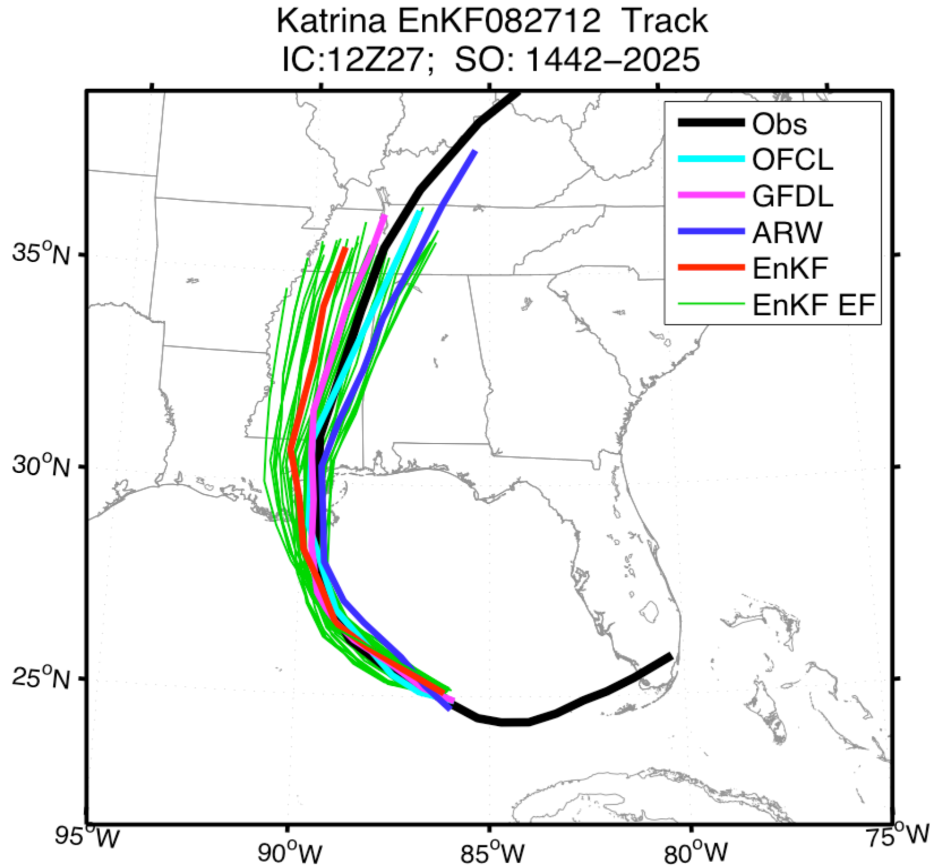
30-member ensemble forecast from EnKF posterior uncertainty

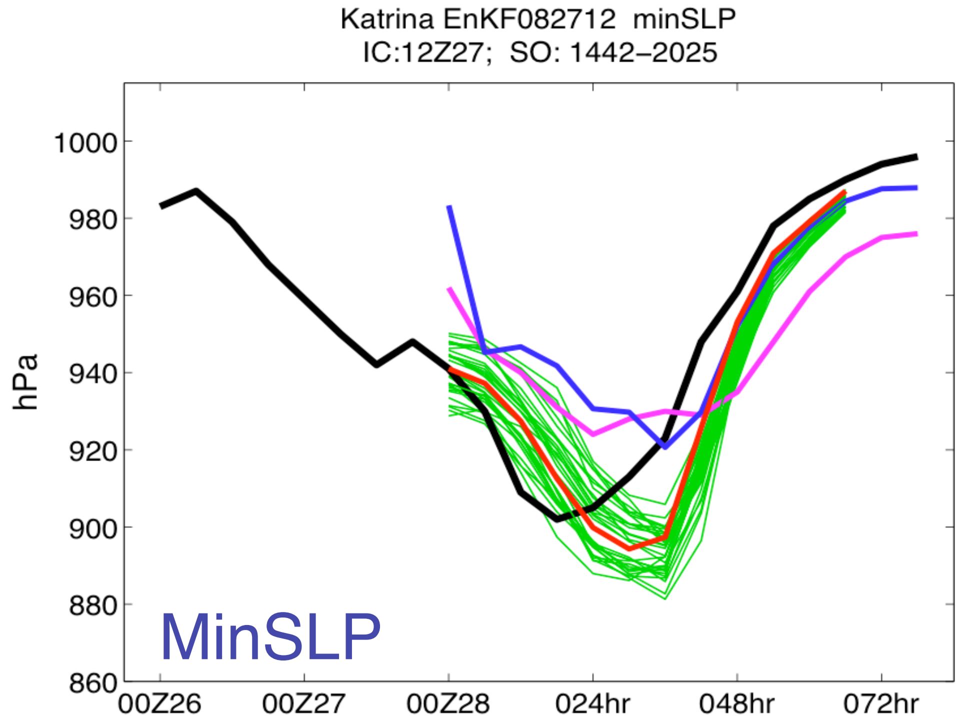


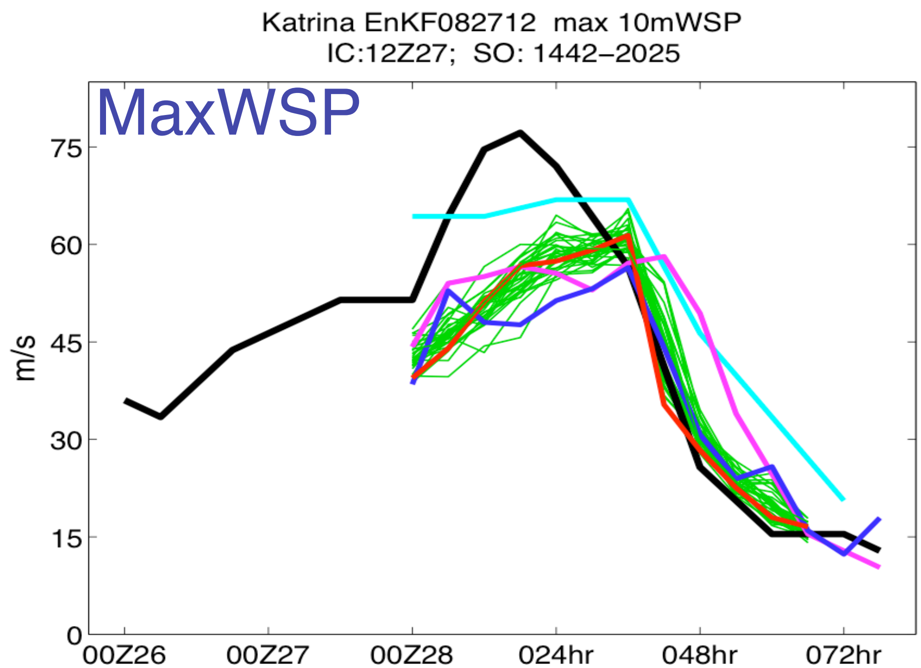




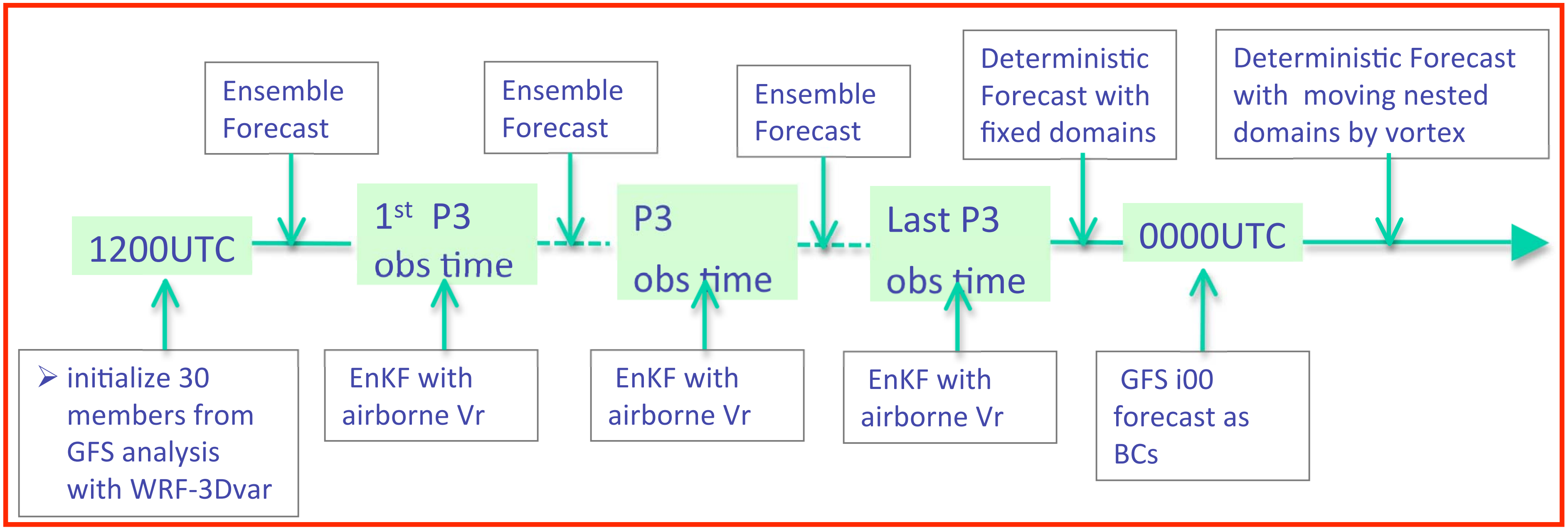
WRF/EnKF Performance (after Florida Landfall)







Assimilation and Forecasts: Work Flow and Timing for 2008/2009 Real-time Experiments



<u>Estimated real-time WRF/ARW forecast initialized assimilating airborne Vr data</u>

EnKF ensemble initialized with most recent available GFS: no waiting time

Quality control and super-observation (SO) of Airborne data per hour: 0.3h

Transfer airborne ~3000 SOs from P3 to TACC: 0.2h

EnKF assimilation of 1-h SOs: 0.5h

126-h WRF free forecast with 512 processors: 2.7h

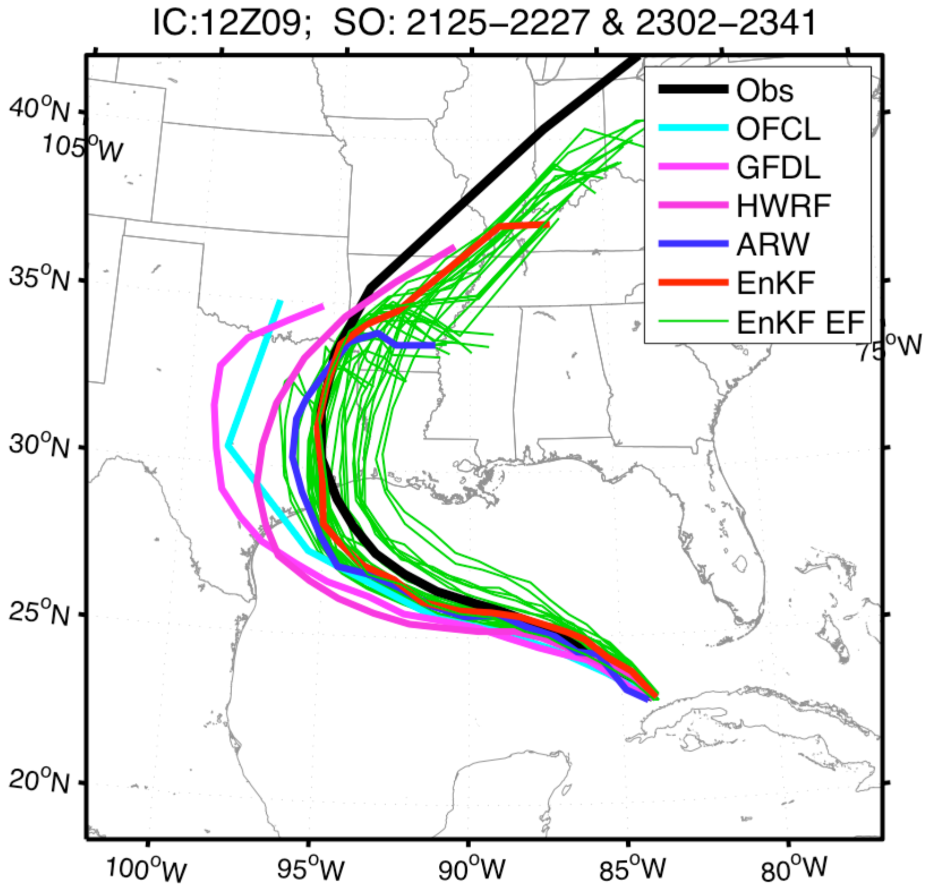
Total time lapse: ~4h for 4.5km (7h for 1.5-km) after Doppler observations are taken

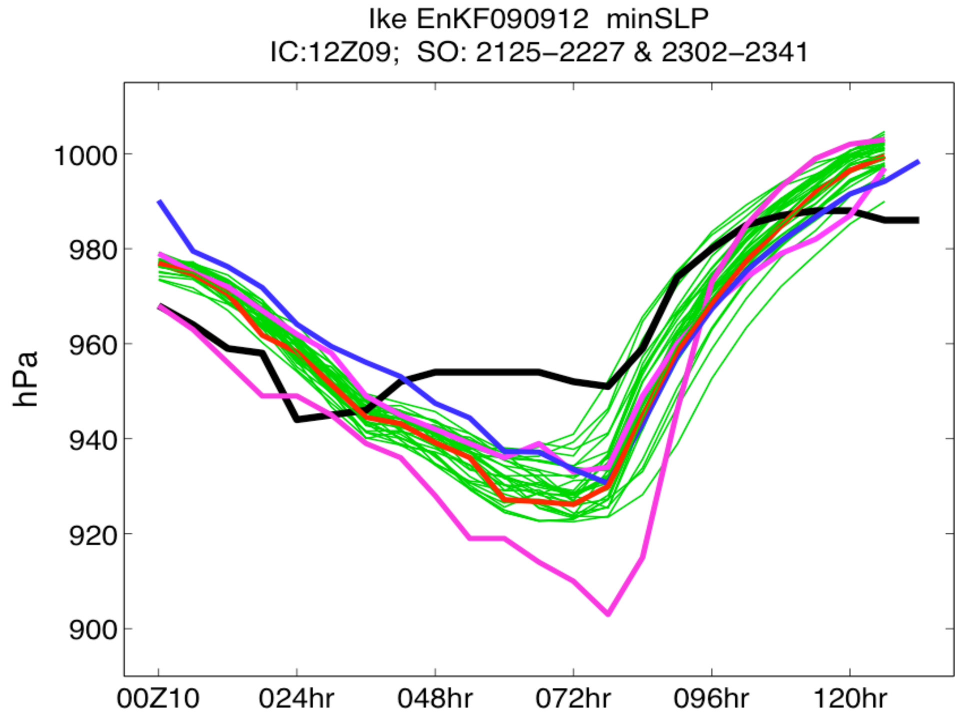
Total Ranger Service Units (SUs) occupied simultaneously: 20,000+

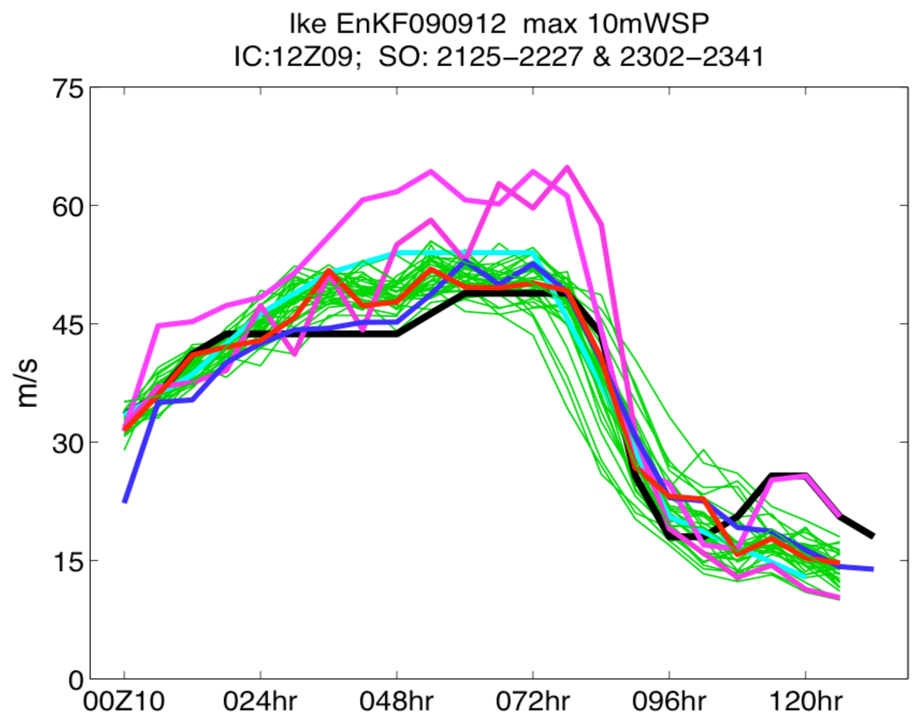
Hurricane IKE (2008)

Realtime EnKF assimilation of airborne Doppler winds

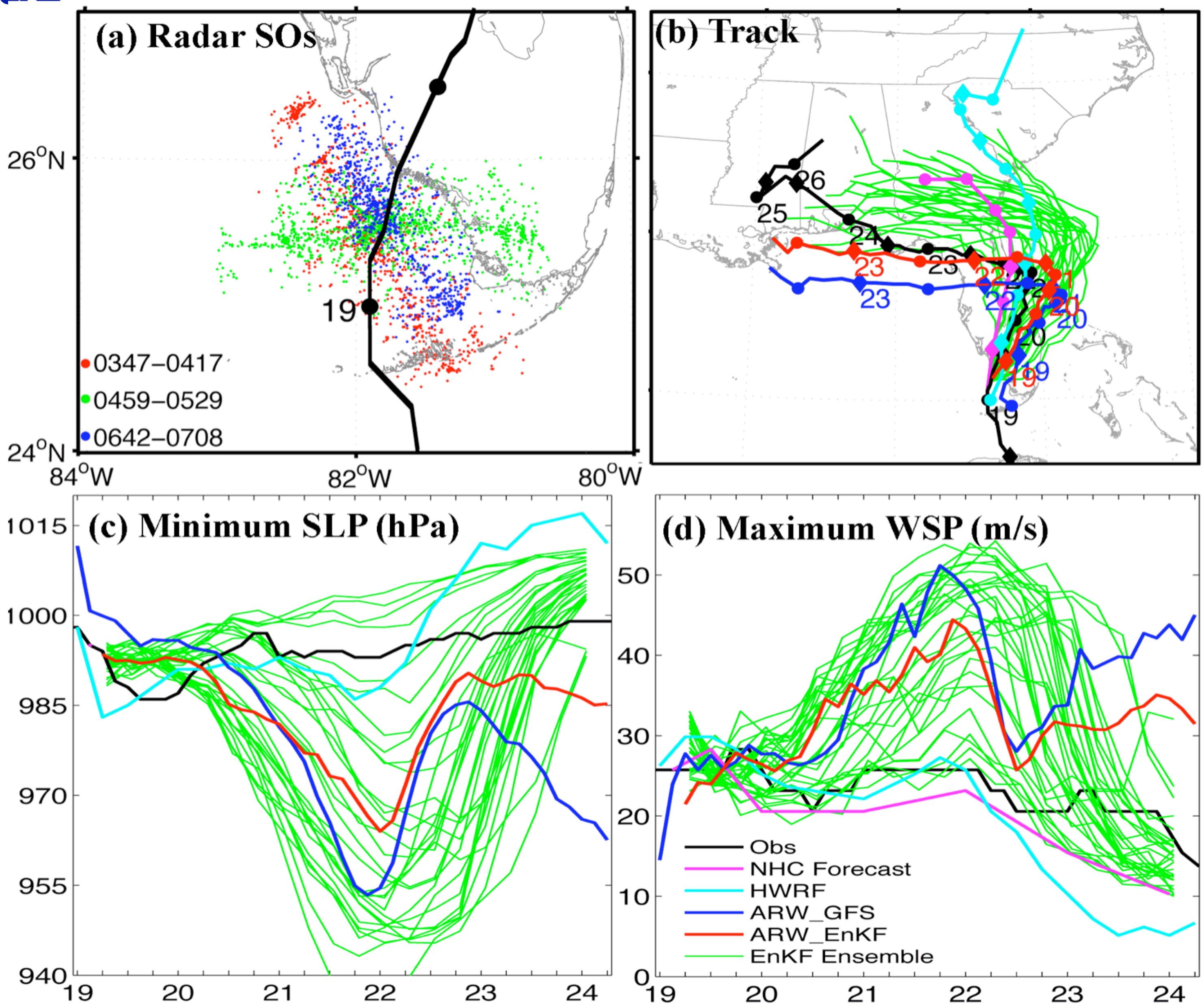
Ike EnKF090912 Track



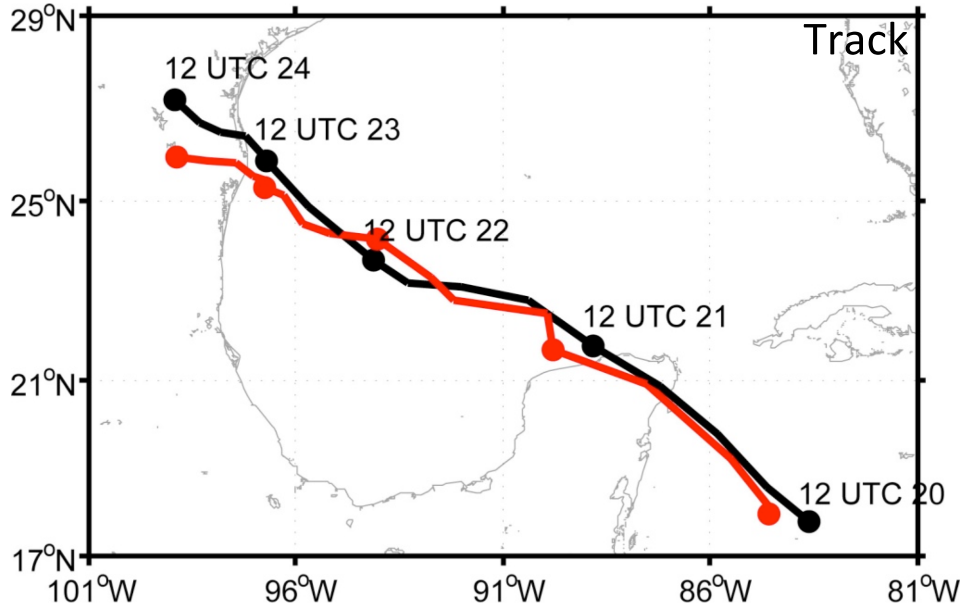




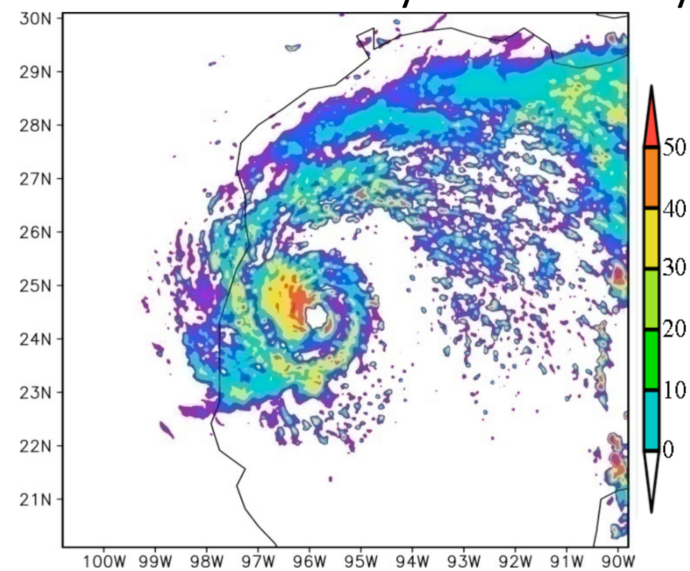
Tropical Storm Fay (2008)
Realtime /EnKF assimilation of airborne Doppler winds

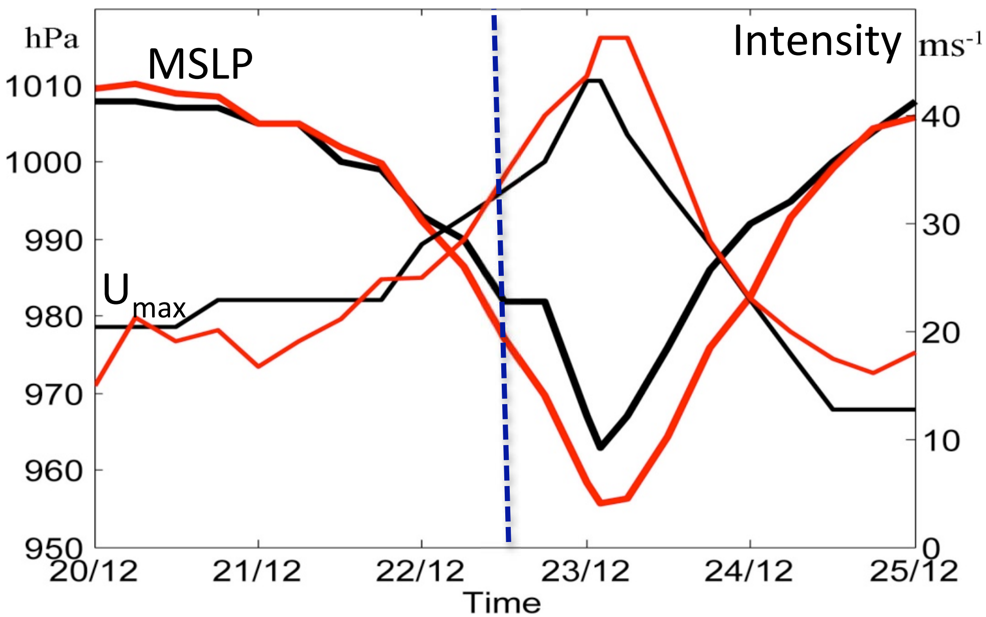


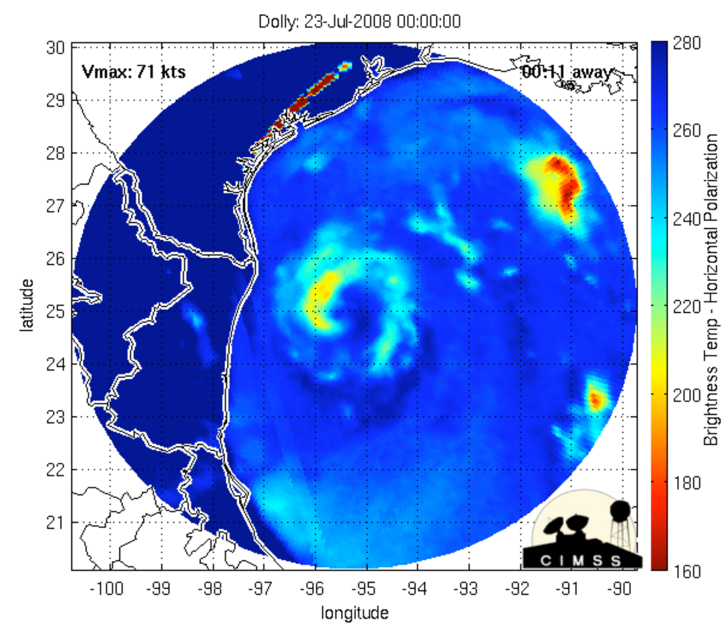
Modeled versus Observed Dolly



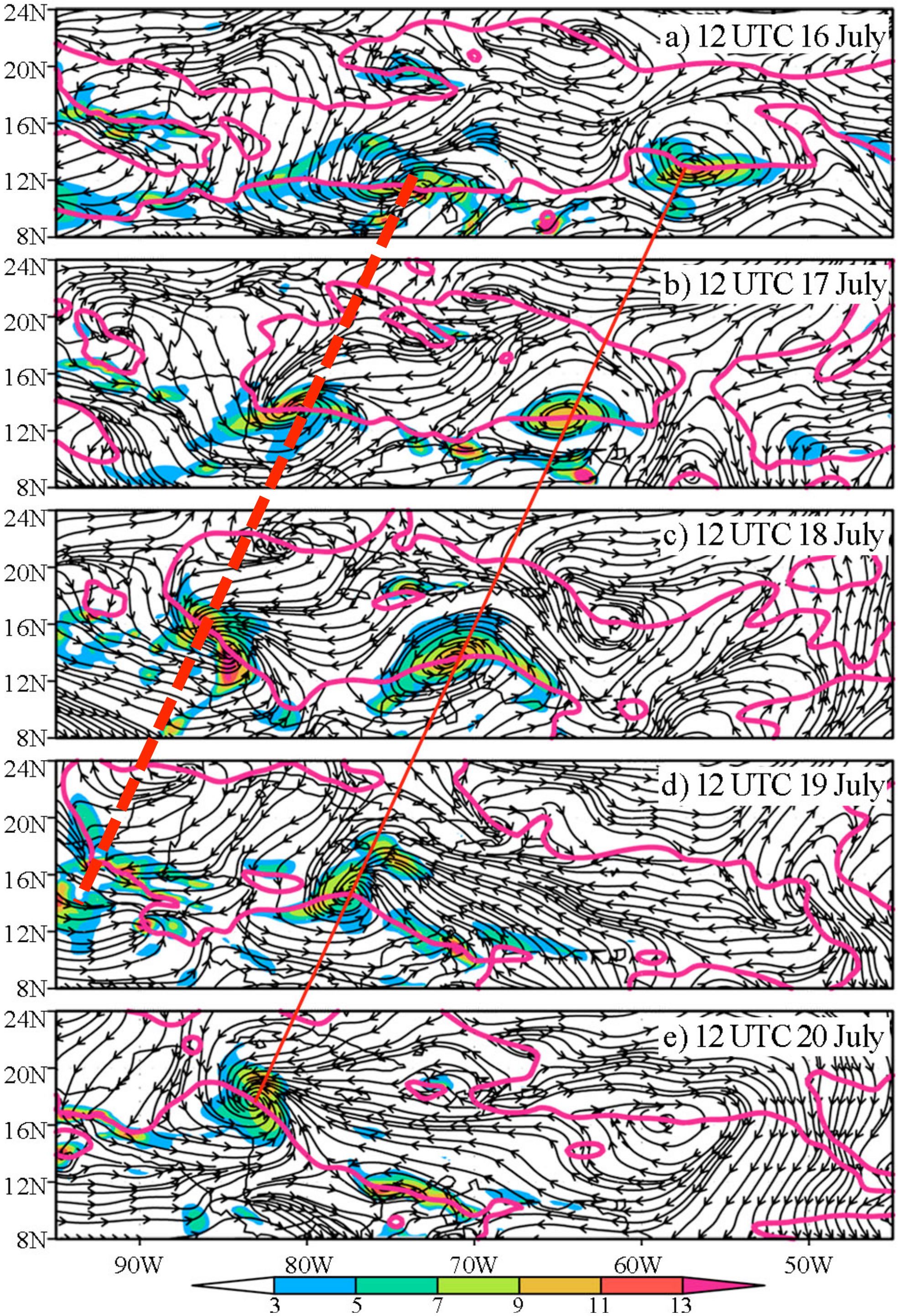
Model Reflectivity at 00Z 23 July







Observed brightness temperature



Easterly Wave Phase

850mb GFS analysis of wave-relativestreamlines, relative vorticity and critical layer

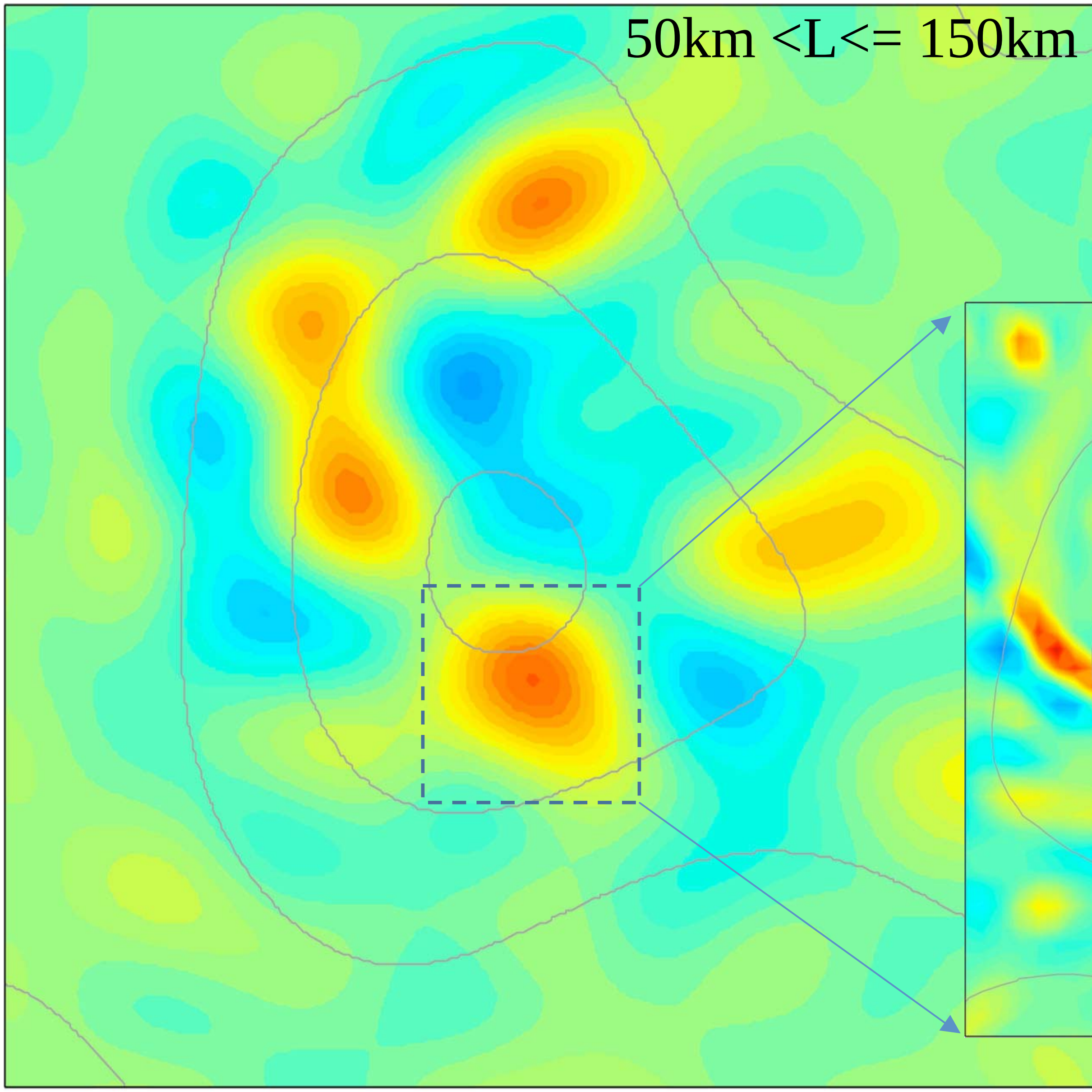
- Easterly wave speed of -7.4m/s
- High vorticity anomaly and continuous moistening within enclosed streamlines ("pouch"; Dunkerton et al. 2008)
- A similar "pouch" preceding incipient Dolly never developed

Cloud-resolving WRF simulation

(Fang and Zhang 2009 JAS)

GFS as IC/BC; 3 nested domains, finest 1.5-km grid 1134x1134km

Multi-scale nature of vorticity anomalies at 39h



(300 km x 300 km)

2D spectral decomposition

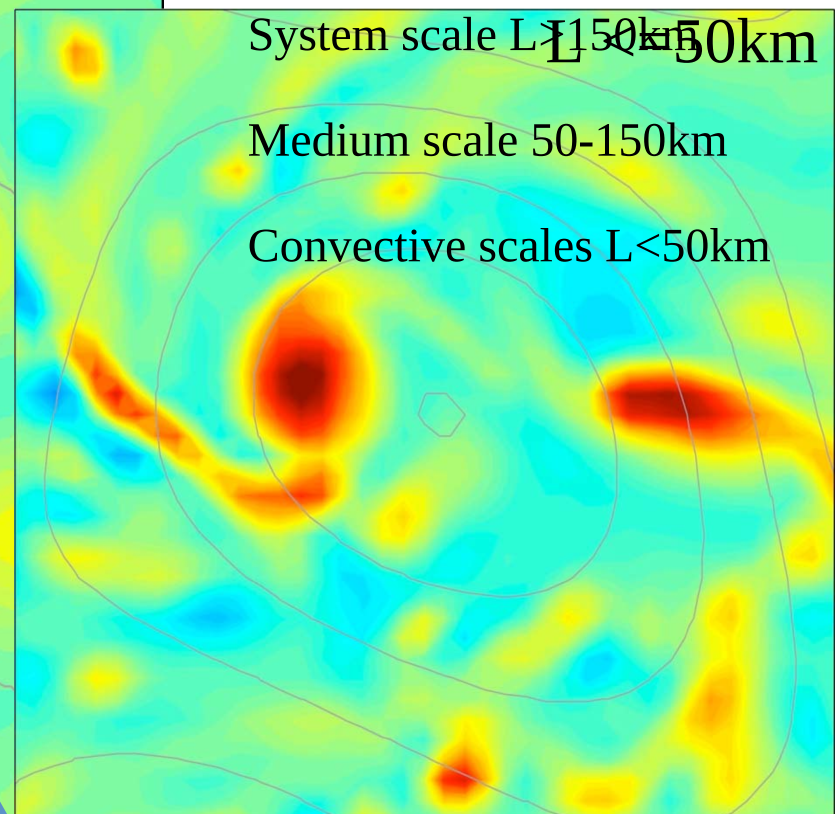
(Lin and Zhang 2008 JAS)

3 characteristic scales:

System scale L>150km

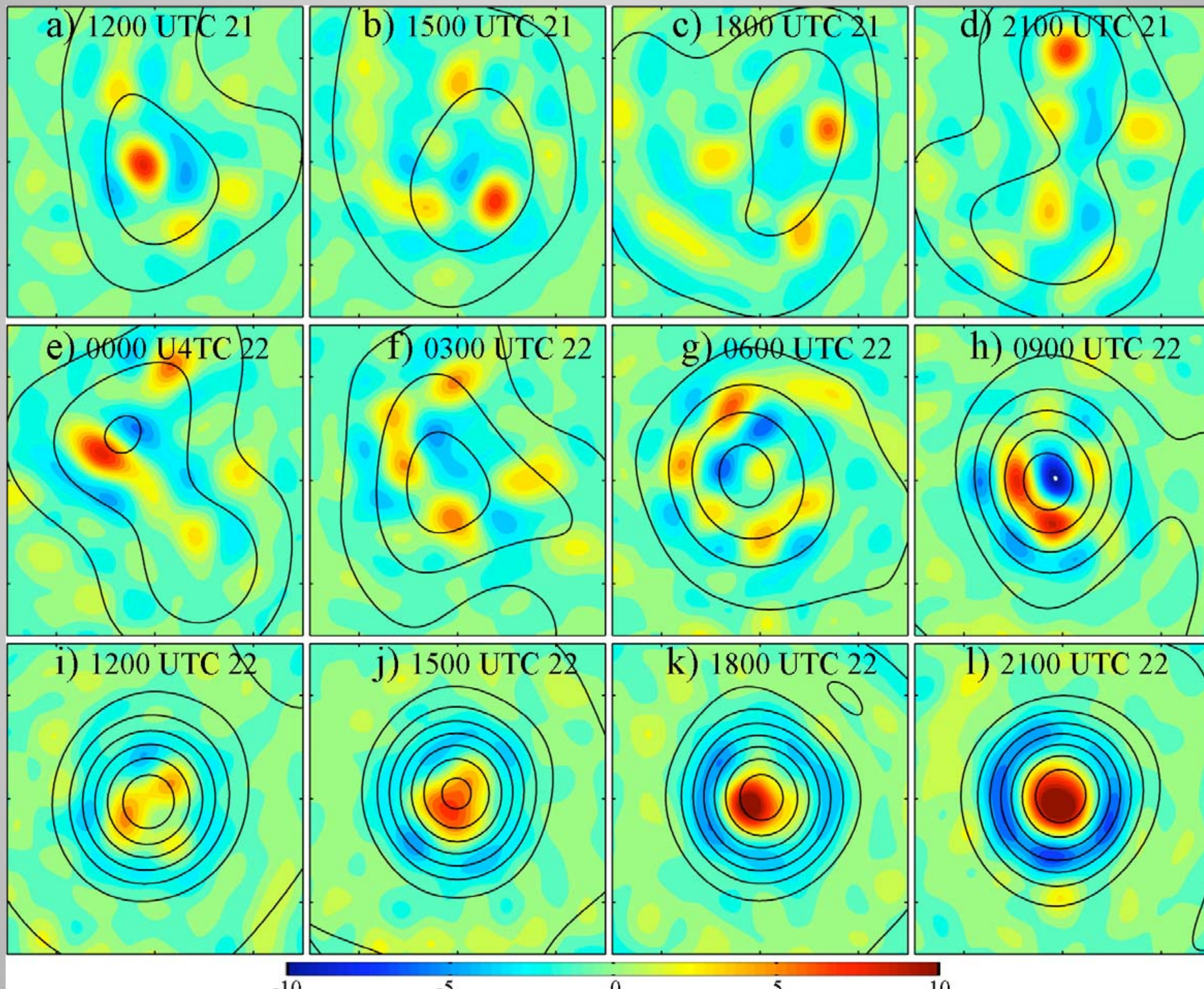
Medium scale 50-150km

Convective scales L<50km



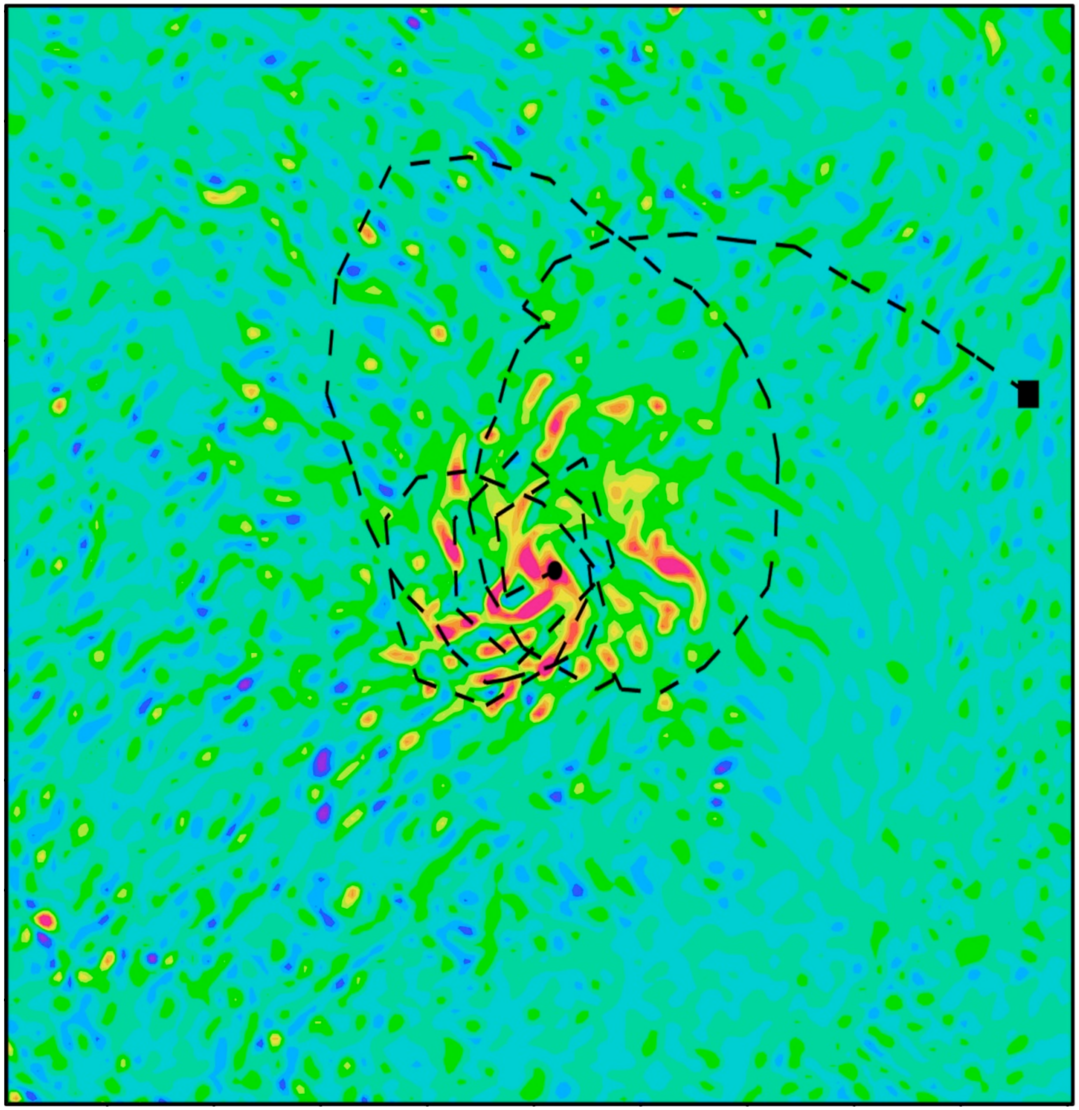
(60 km x 60 km)

System-scale development



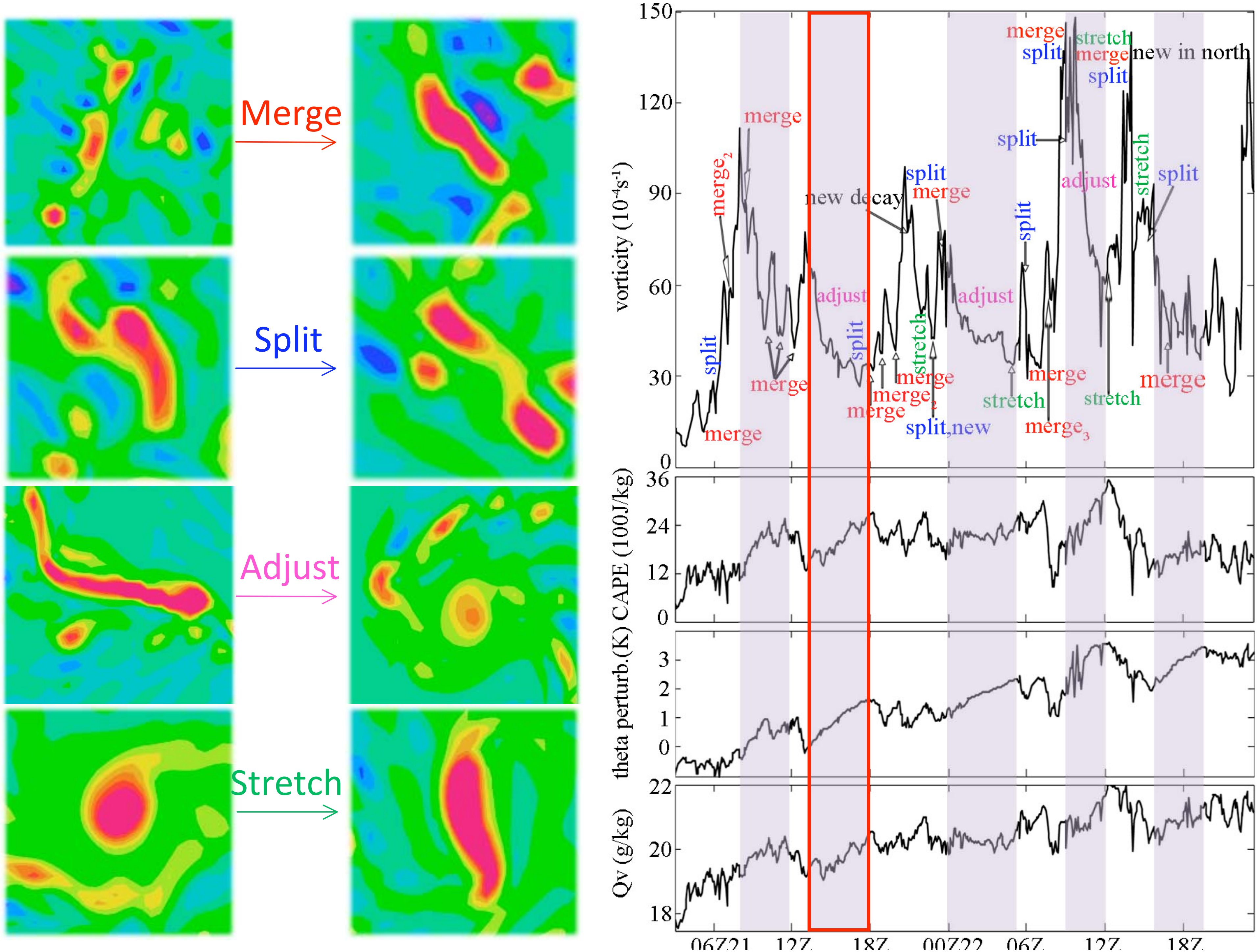
(300 km x 300 km) shading: 50 km<L<=150 km contours: L>150 km

Tracking of a vorticity anomaly from 39 h to 52 h



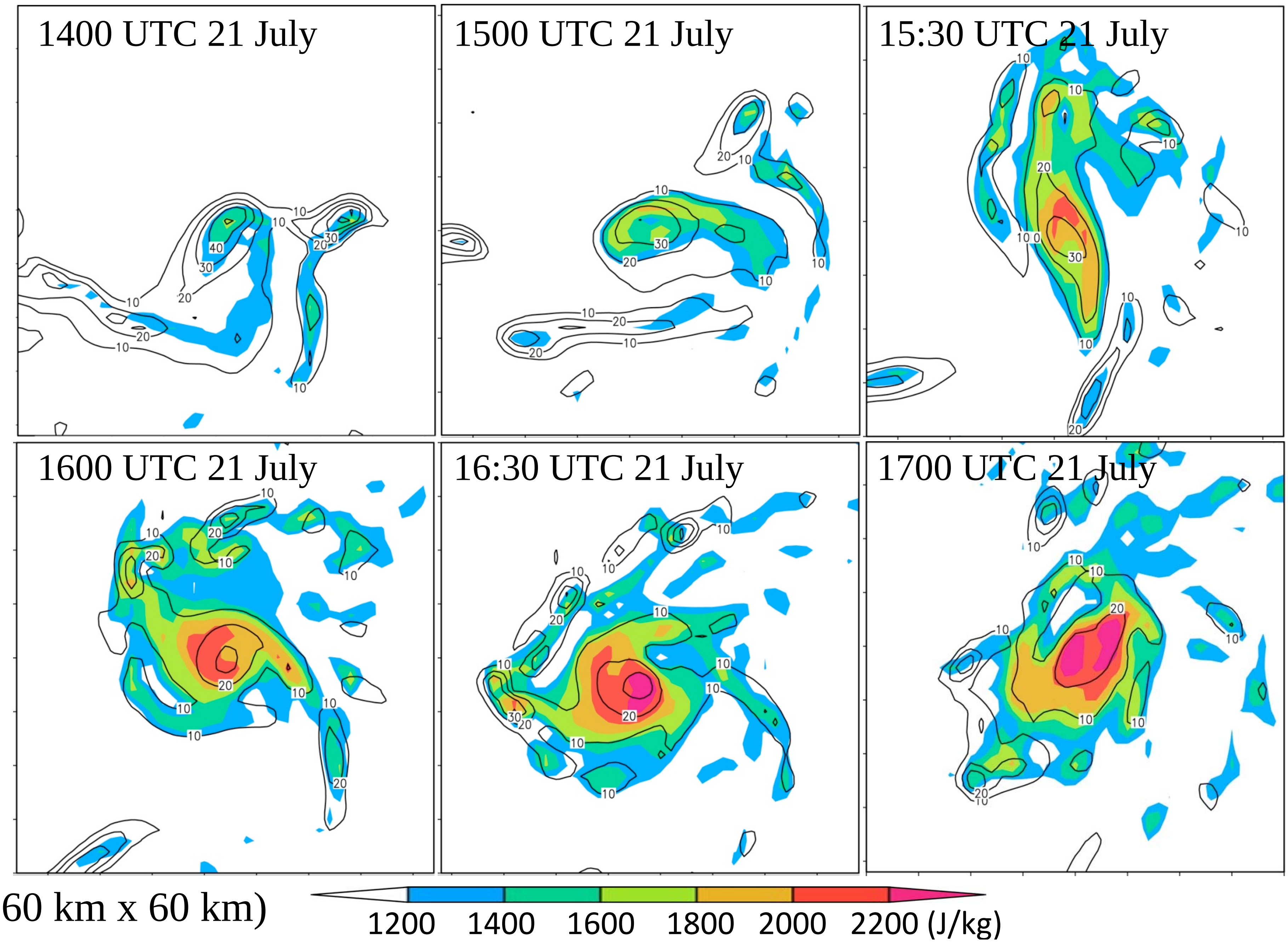
(300 km x 300 km, every 5 minutes)

Strongest
Long lasting



Merge
Split
Adjust
Stretch
vorticity ($10^{-4}s^{-1}$)
CAPE (100J/kg)
theta perturb.(K)
Qv (g/kg)
06Z21
12Z
18Z
00Z22
06Z
12Z
18Z
merge
split
adjust
stretch
new decay
new in north
split,new

Vorticity (contour, $10^{-4}s^{-1}$) and CAPE (shading) associated with VHT-210304

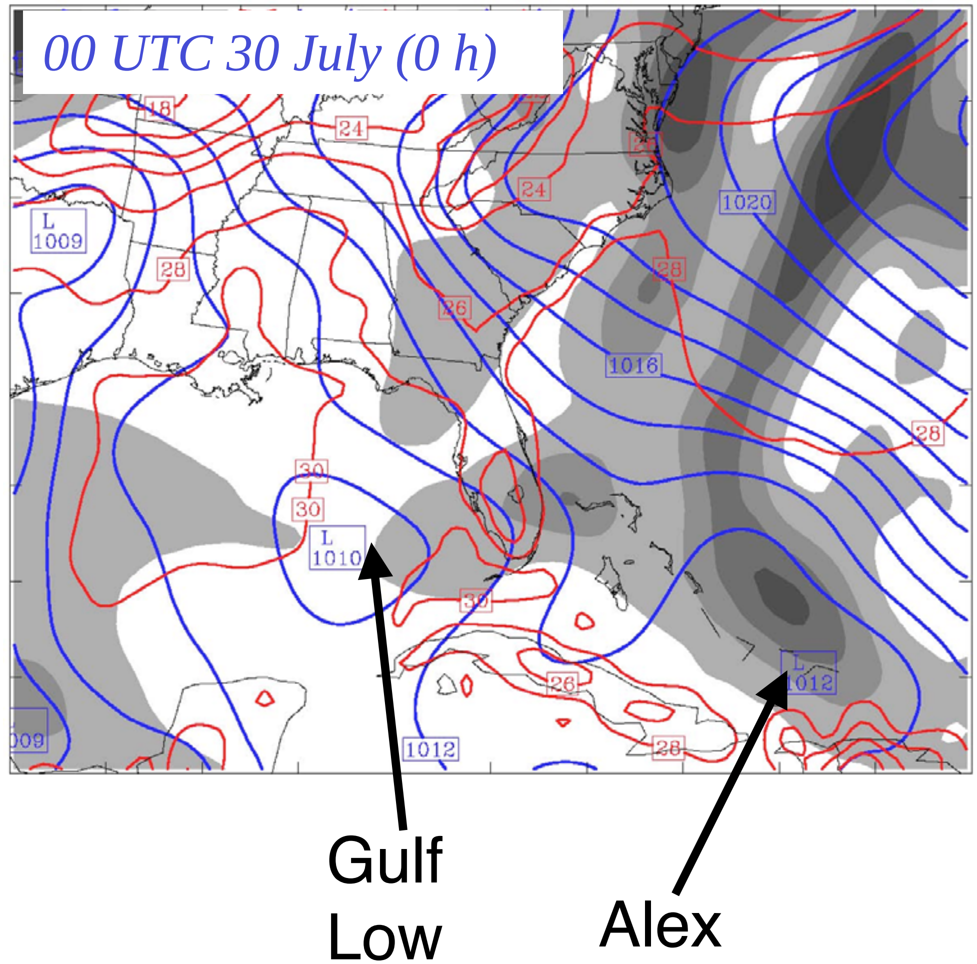


(60 km x 60 km)

Predictability of a 2004 Gulf of Mexico Disturbance

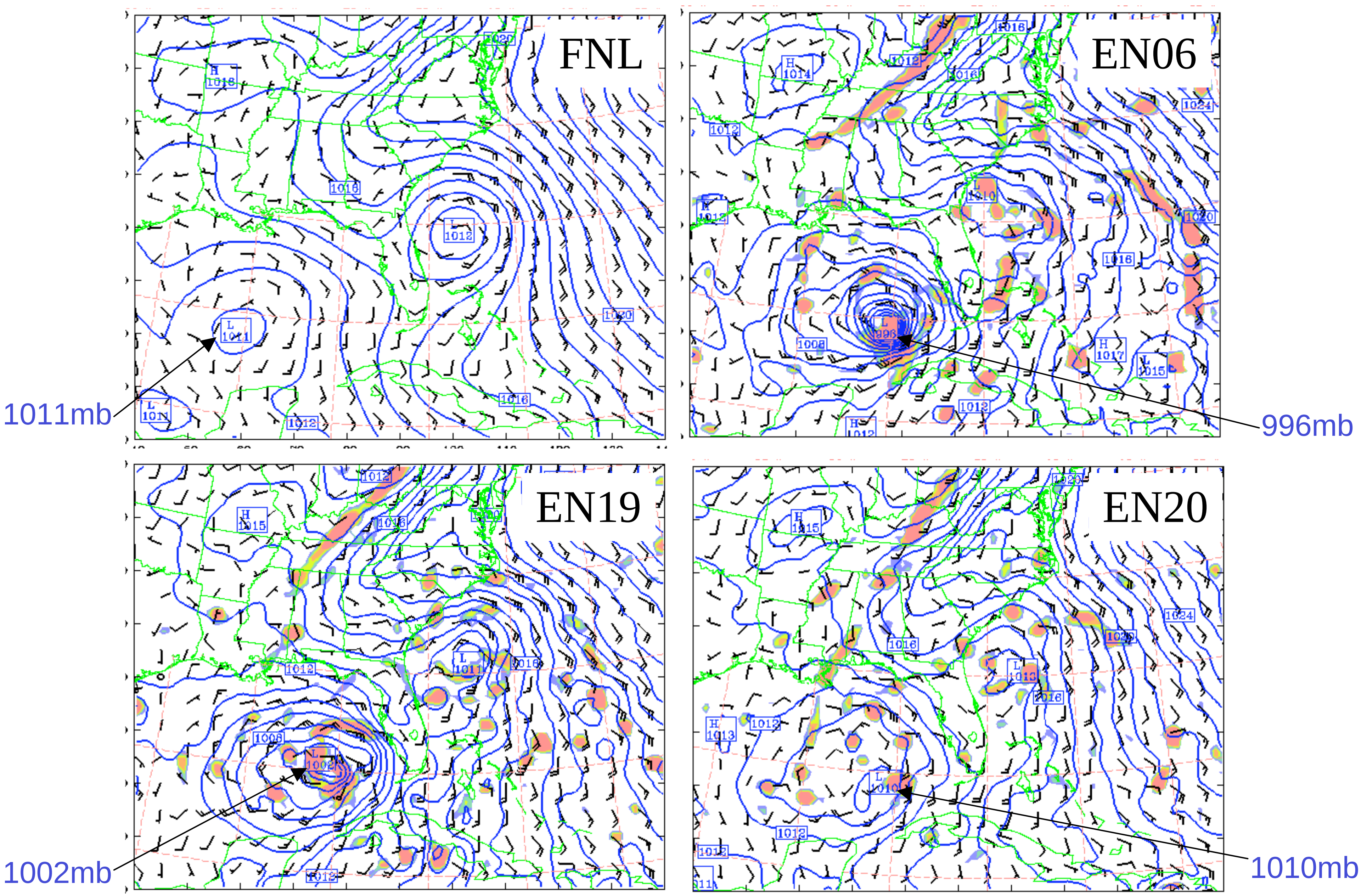
- **West-moving disturbance**
- **Slight intensification on 7/29**
- **Favorable environment (similar to that of pre-Alex)**
- **Forecasters thought it would be "the one" to develop**
- **Never attained TD status but *could've been Alex***

SLP, sfc T and 200hpa PV



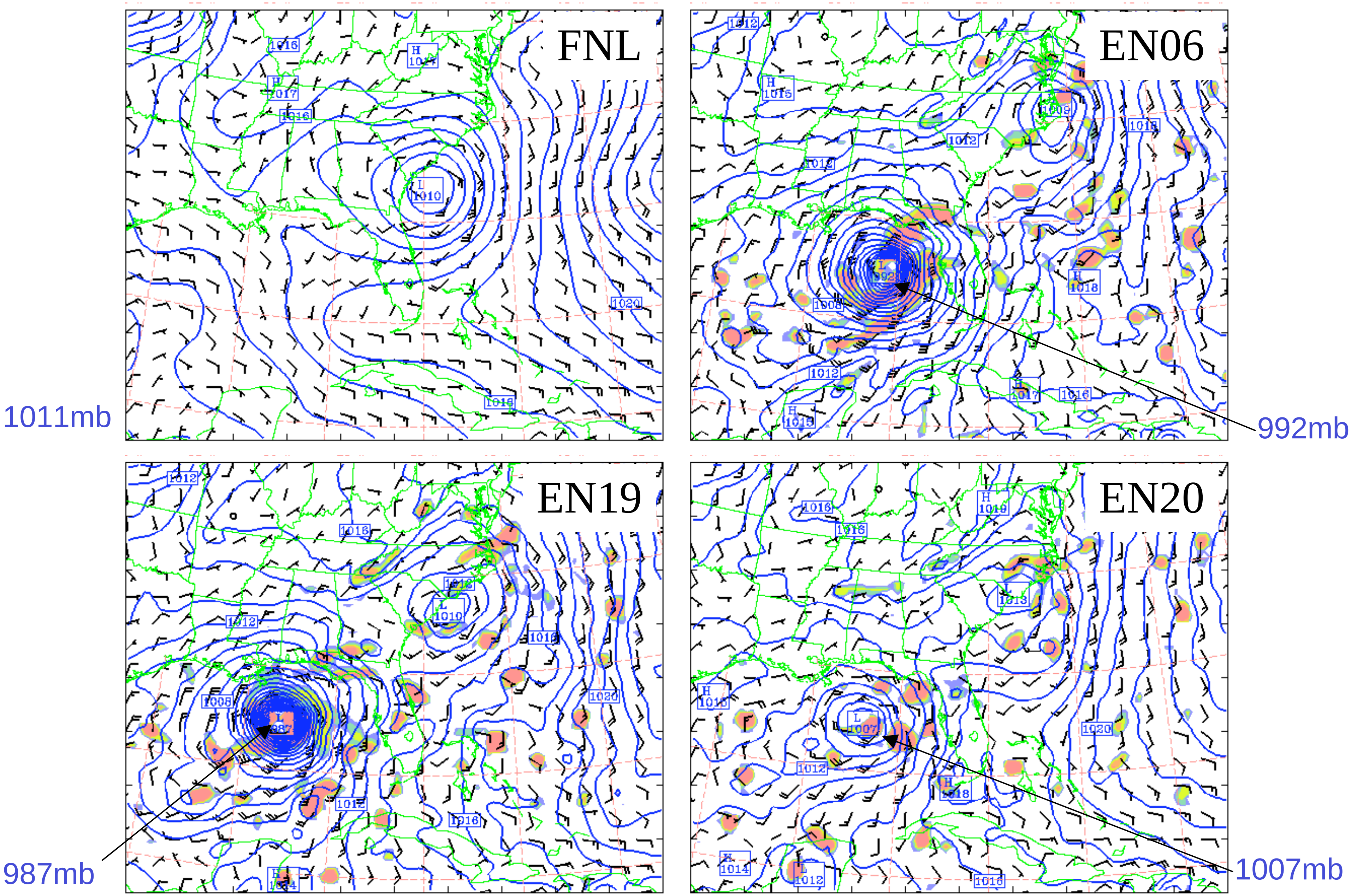
(Sippel and Zhang 2009b JAS; Zhang and Sippel 2009 JAS)

FNL analysis and ensemble members #6, 19, 20 valid at 36h



(Sippel and Zhang 2009b JAS; Zhang and Sippel 2008 JAS)

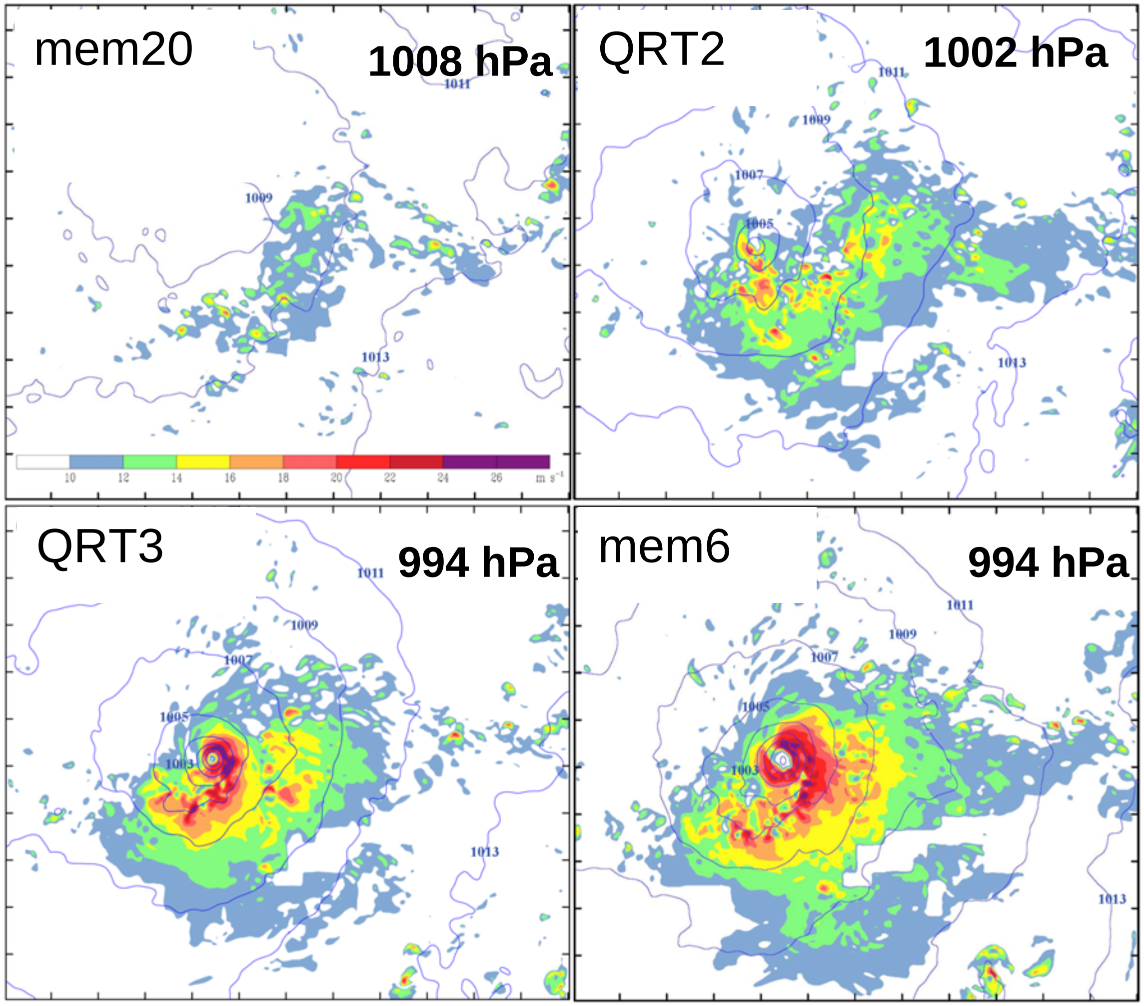
FNL analysis and members #6, 19, 20 valid at 72h



(Sippel and Zhang 2009b JAS; Zhang and Sippel 2009 JAS)

Gulf low: Sensitivity study

- **Limit of intrinsic predictability**
  - **Simulated storms can be *very sensitive* to practically *immeasurable* changes in ICs**

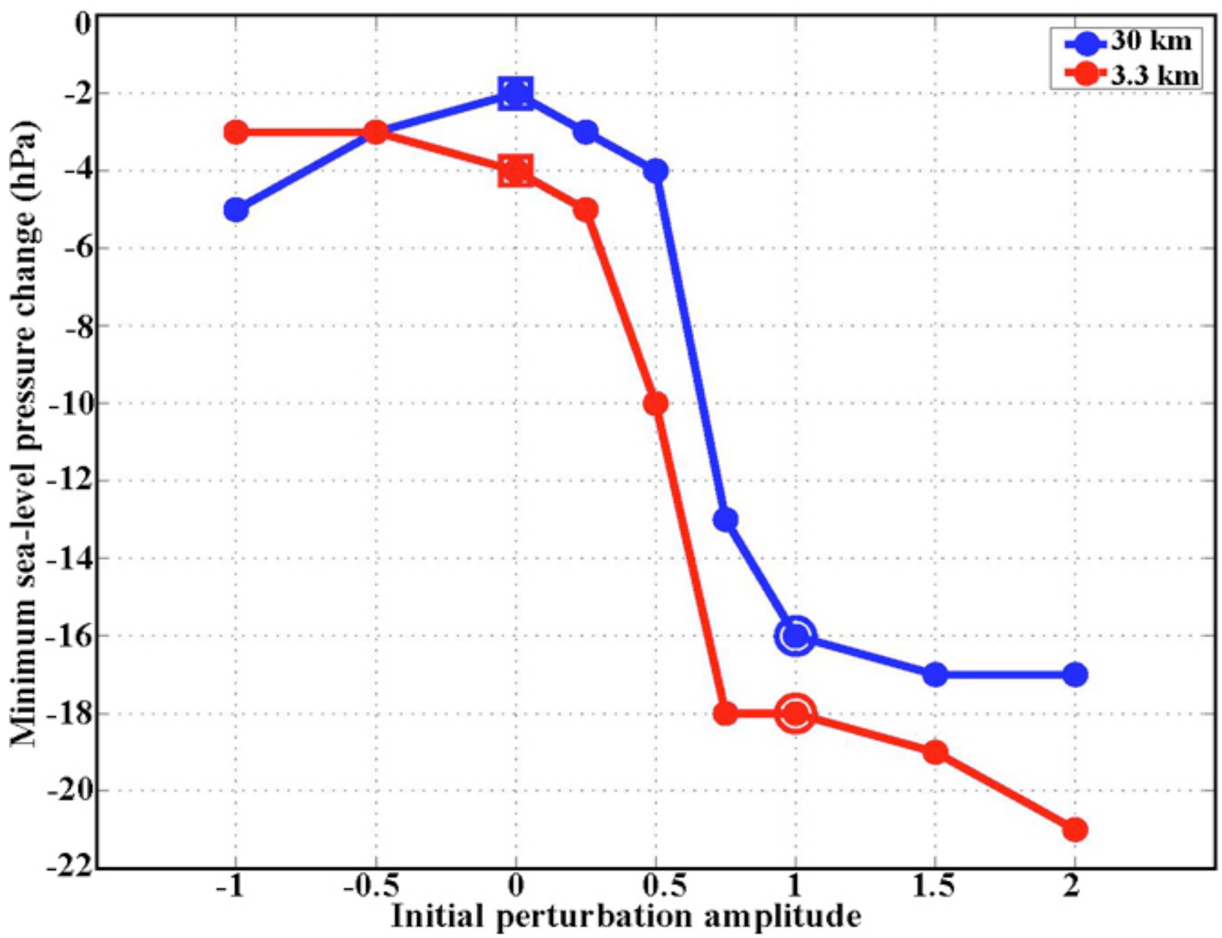


Winds every 2 m/s above 10 m/s; Pressure every 10 hPa

(Zhang & Sippel 2009, JAS)

Gulf low: Limit of Intrinsic Predictability

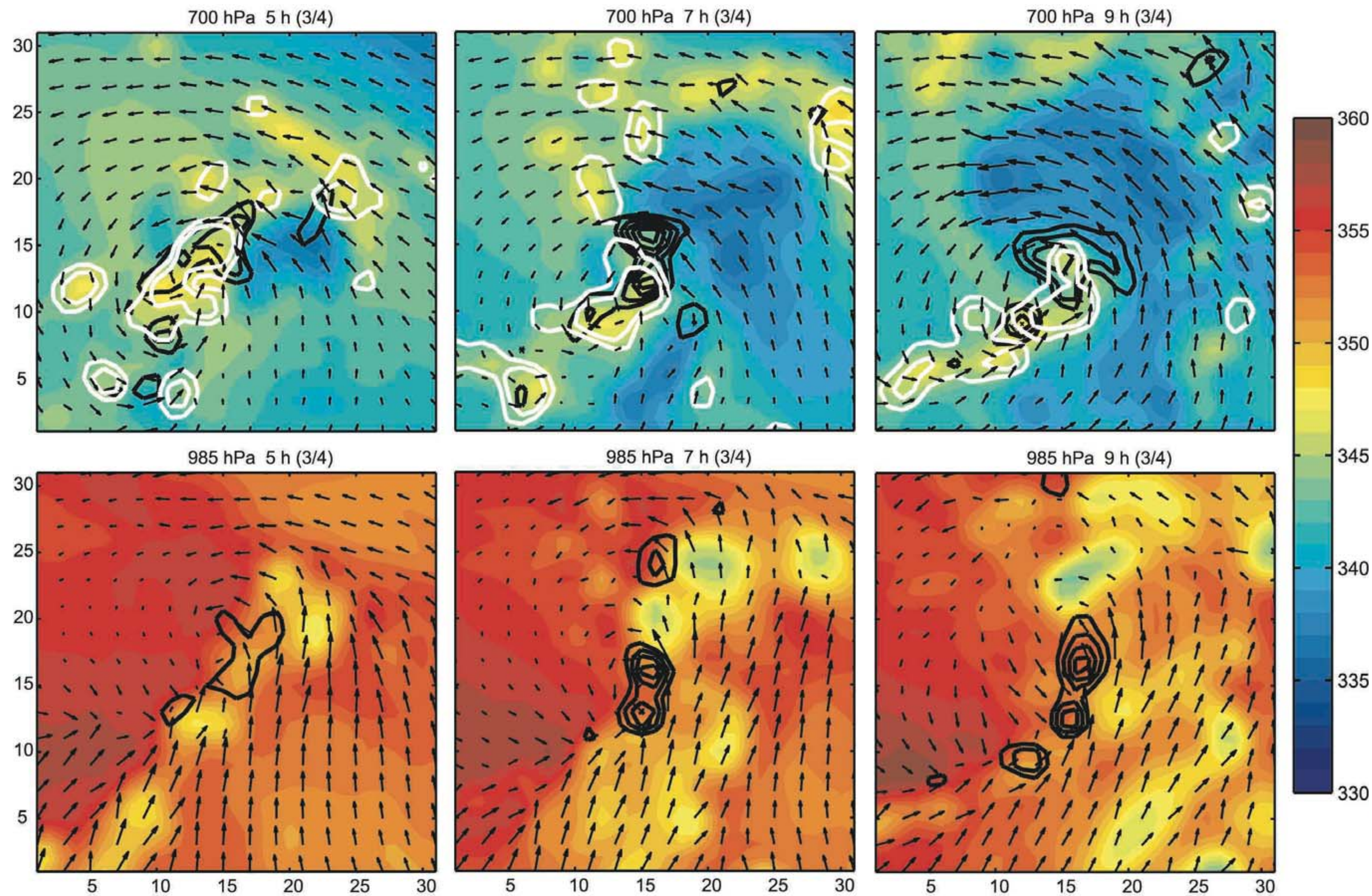
- Simulated storms can be *very sensitive* to *immeasurable* changes in ICs
- How do previous findings on impact of moist convection manifest themselves to result in large responses to small IC differences?



Sensitivity of 36-h MSLP change forecast to IC differences by linearly rescaling the initial difference between ensemble members #20 (0) and #6 (1)

(Zhang and Sippel 2009 JAS)

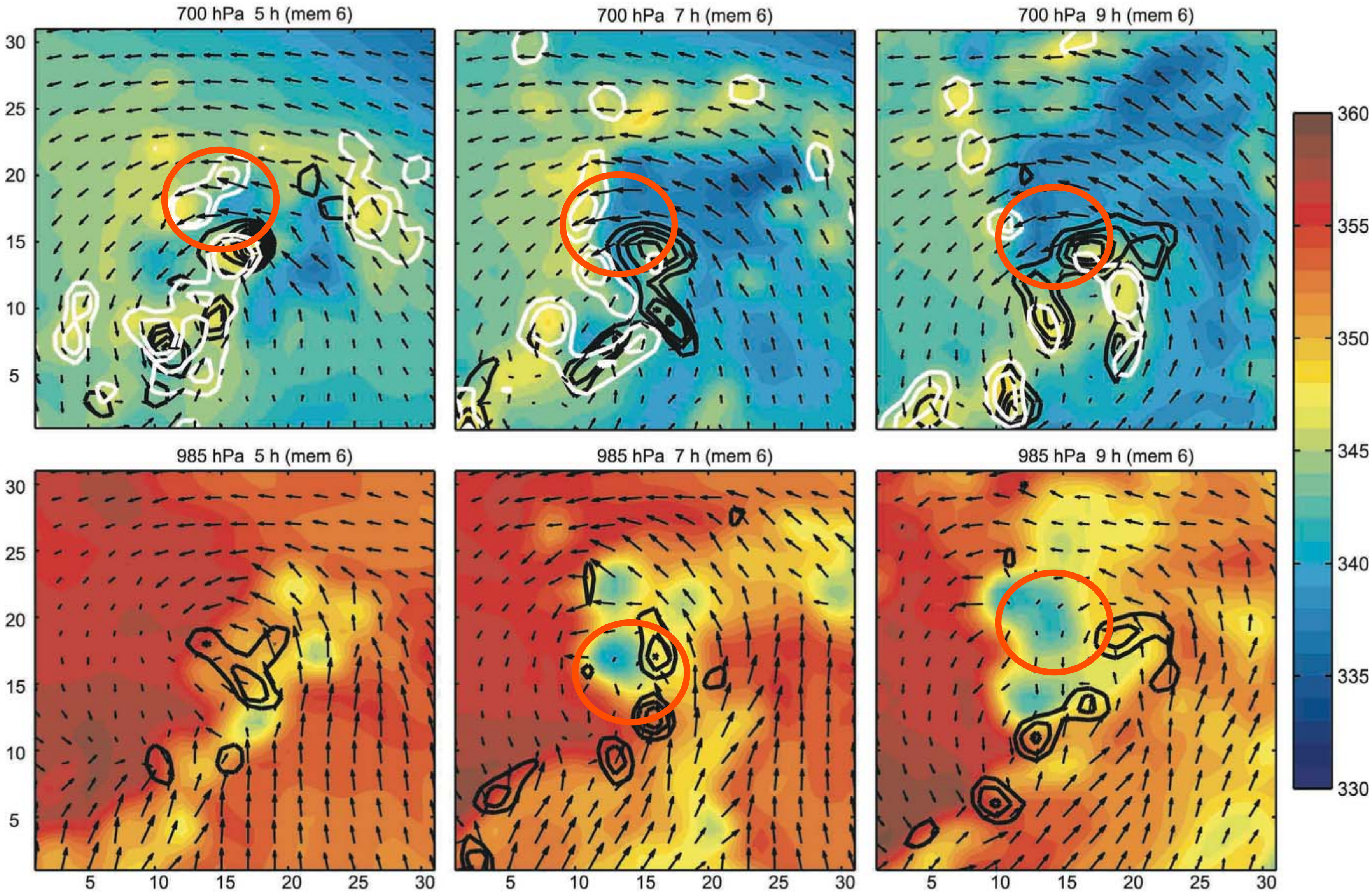
Gulf low: Cold pool interaction with VHTs -EXP(3/4)



Color: theta-e Black Contour: vorticity (every .00025 s^-1) White Contour: w (every 0.5 m/s)

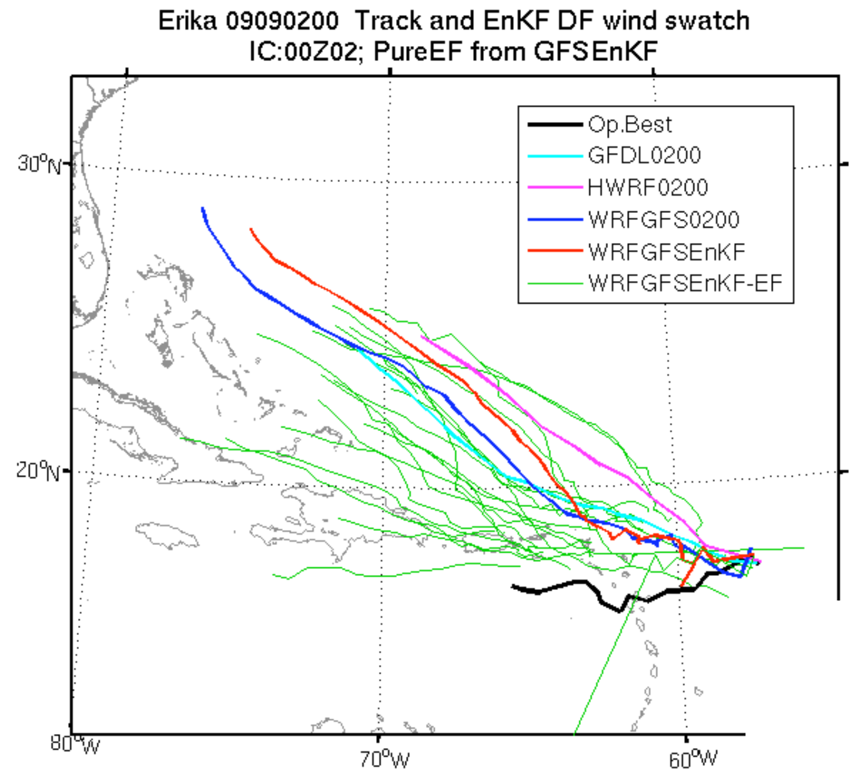
(Zhang and Sippel 2009 JAS)

Gulf low: Cold pool interaction with VHTs - #6(1)



Color: theta-e Black Contour: vorticity (every .00025 s^-1) White Contour: w (every 0.5 m/s)

(Zhang and Sippel 2009 JAS)


Erika 09090200 Track and EnKF DF wind swatch
IC:00Z02; PureEF from GFSEnKF
Op.Best
GFDL0200
HWRF0200
WRFGFS0200
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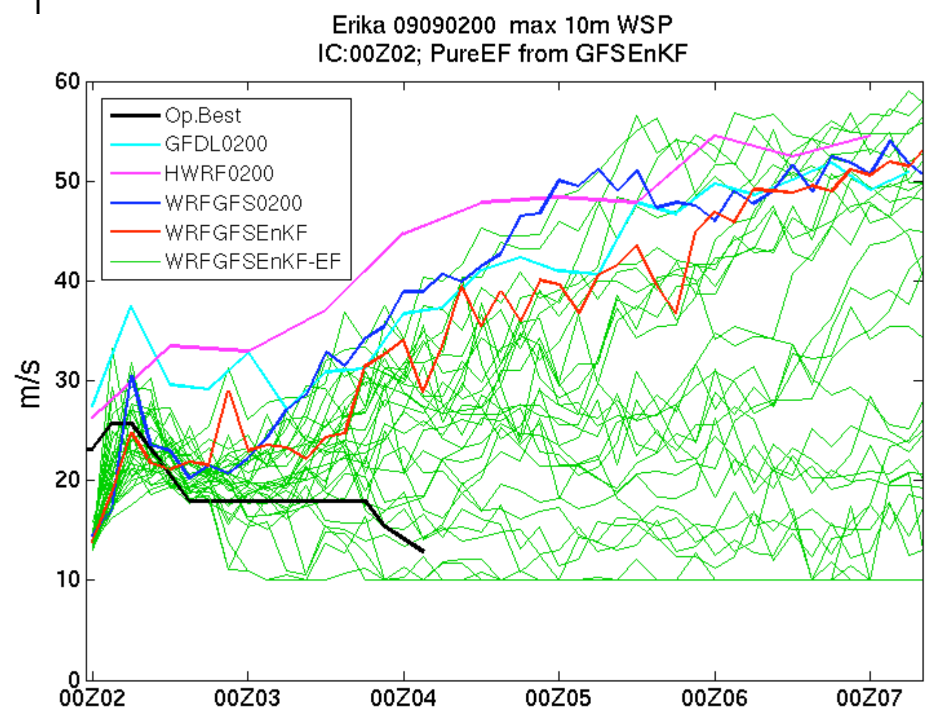
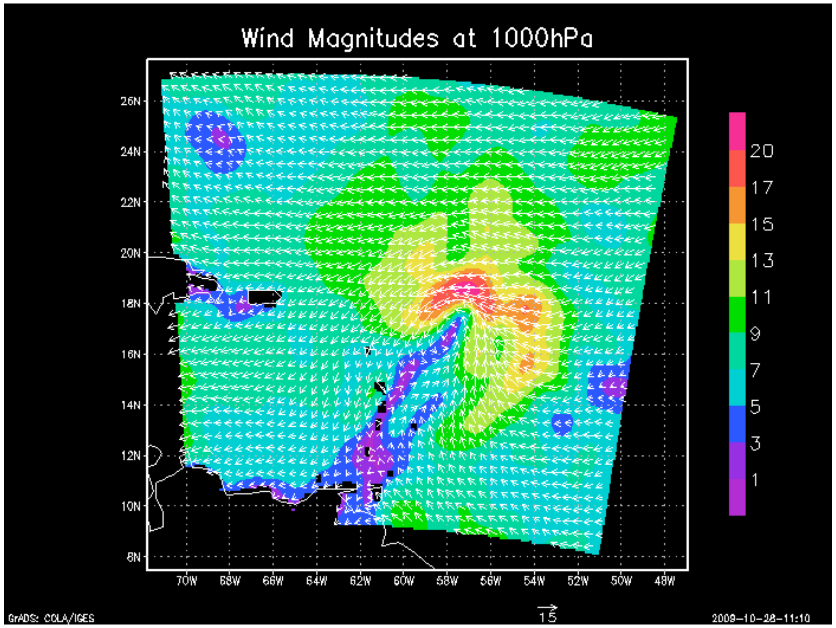
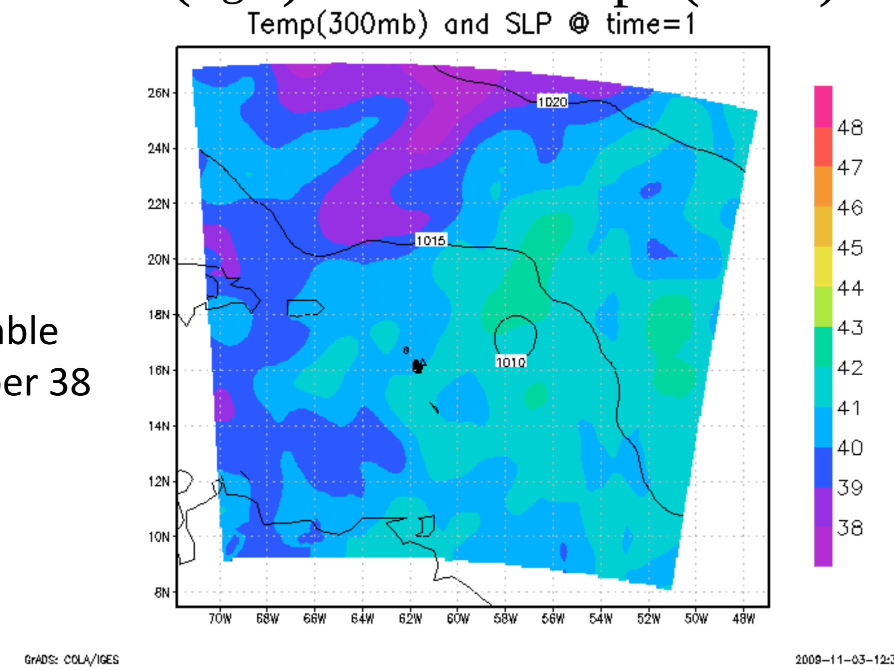
WRFGFSEnKF-EF
30°N
20°N
80°W
70°W
60°W

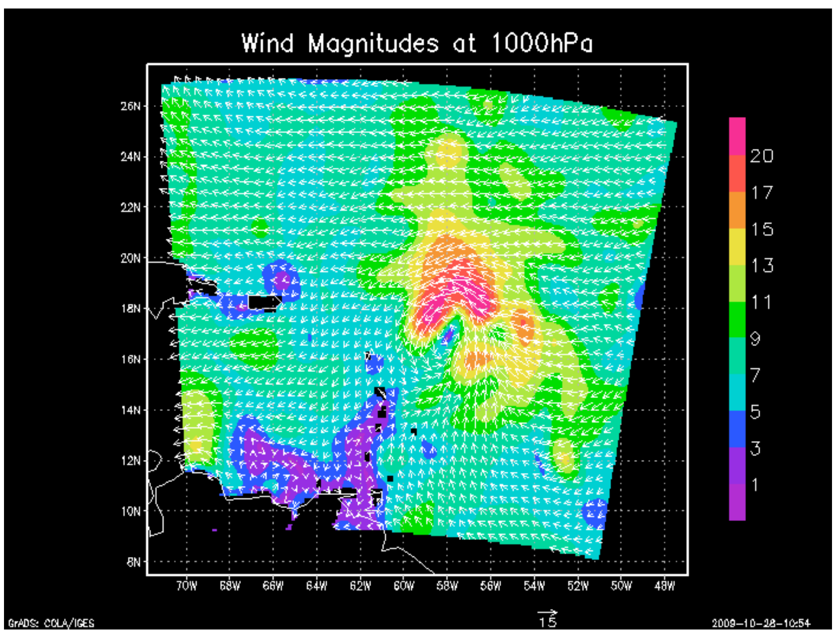

Erika 09090200 max 10m WSP
IC:00Z02; PureEF from GFSEnKF
Op.Best
GFDL0200
HWRF0200
WRFGFS0200
WRFGFSEnKF
WRFGFSEnKF-EF
m/s
0
10
20
30
40
50
60
00Z02
00Z03
00Z04
00Z05
00Z06
00Z07

Surface winds (left) and 300mb temperature (right) at 00Z 2 Sept (t=0h)

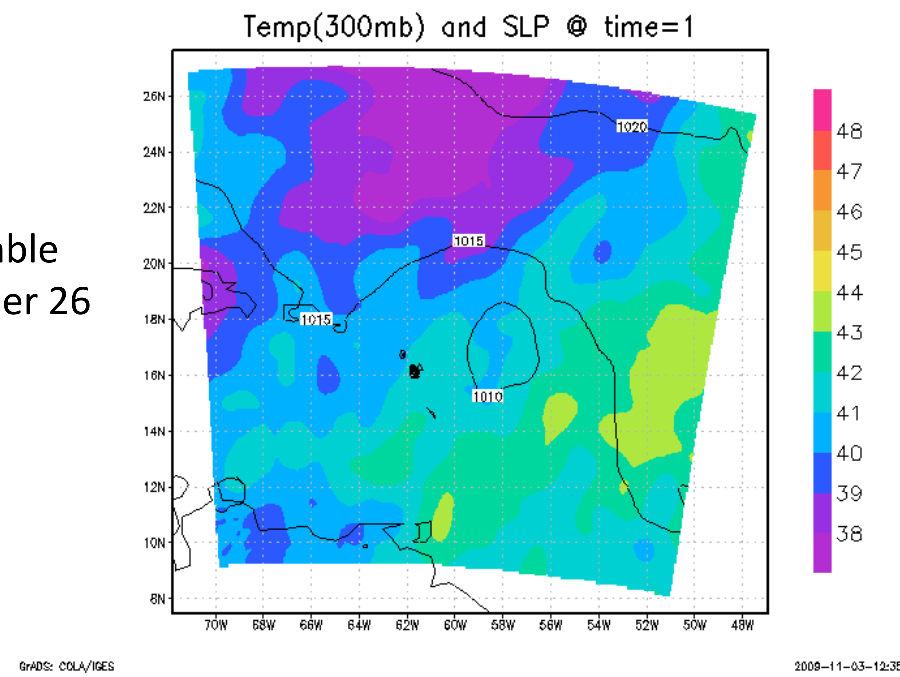


Ensemble member 38

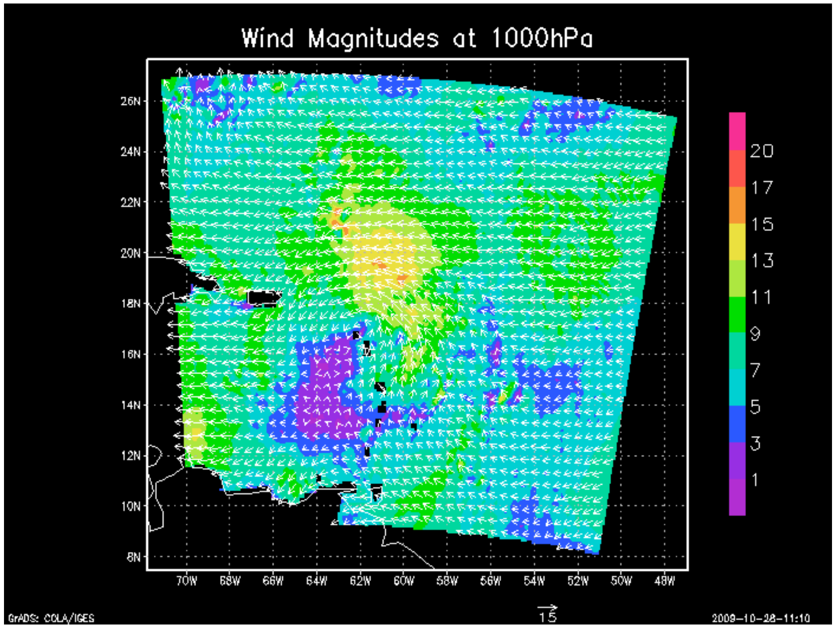




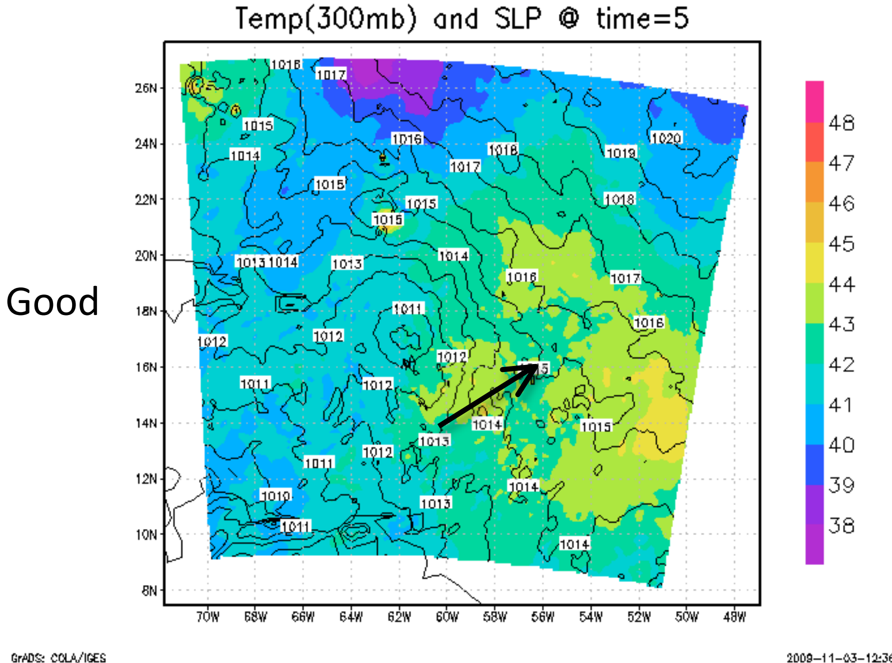
Ensemble member 26

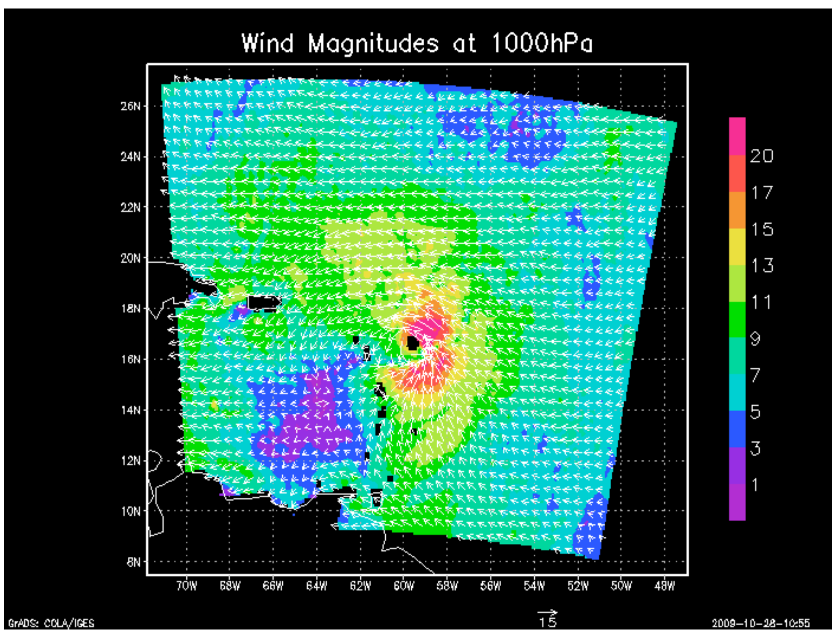


Surface winds (left) and 300mb temperature (right) at t=24h forecast time

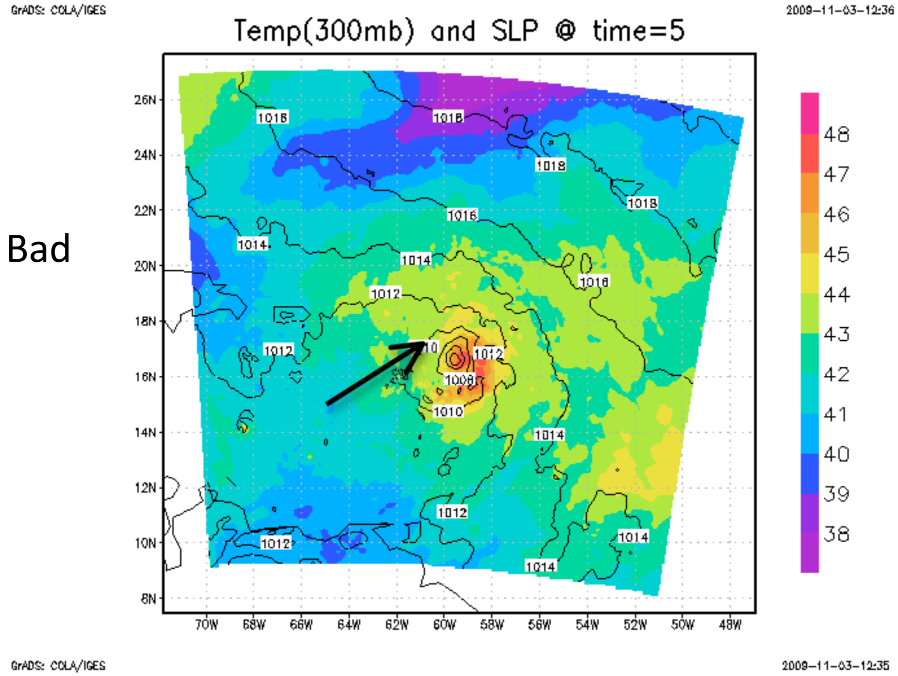


38 - Good

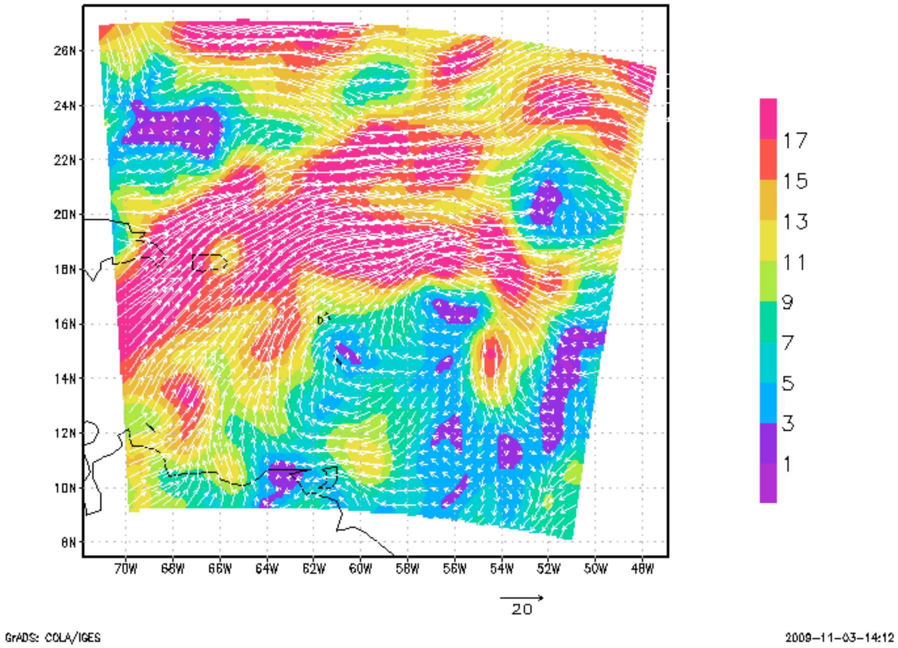




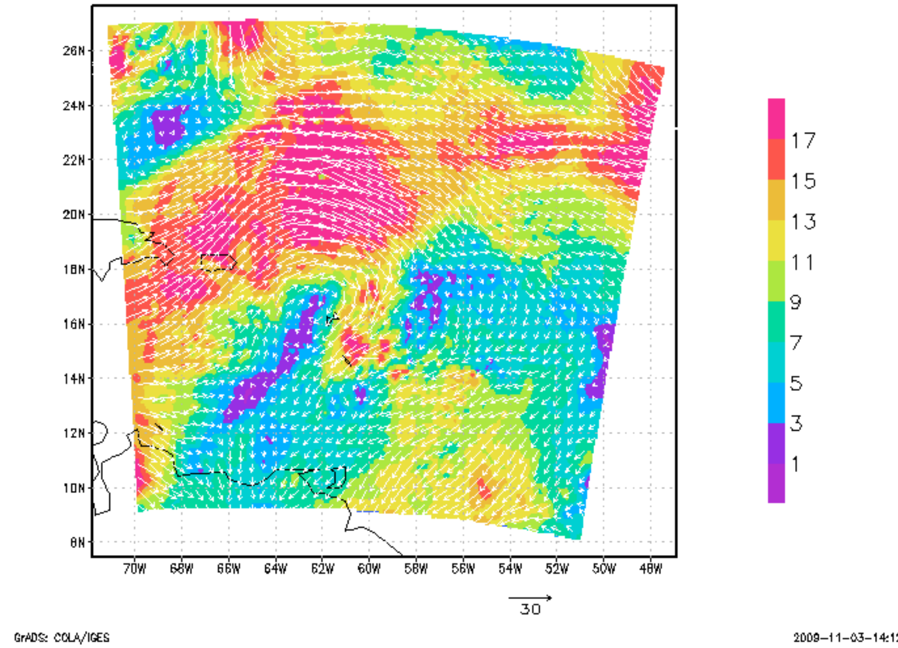
26 - Bad



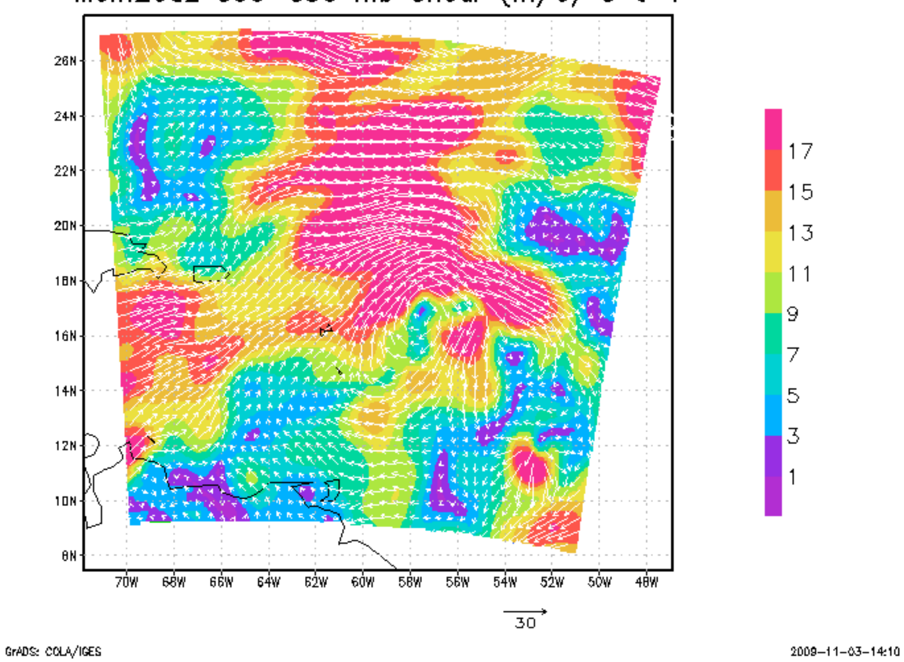
Mem38d2 300-850 mb Shear (m/s) @ t=1



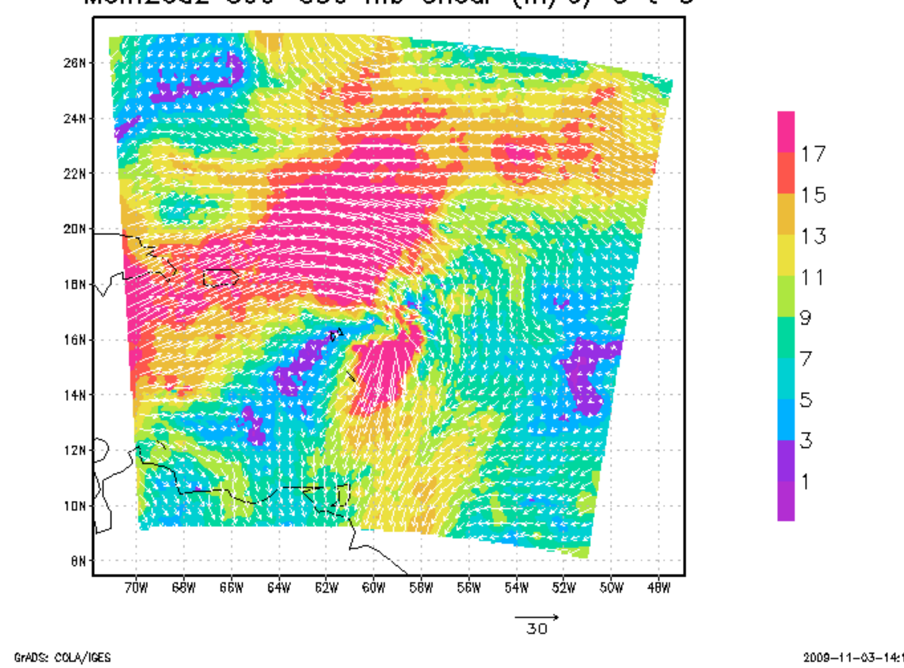
Mem38d2 300-850 mb Shear (m/s) @ t=5

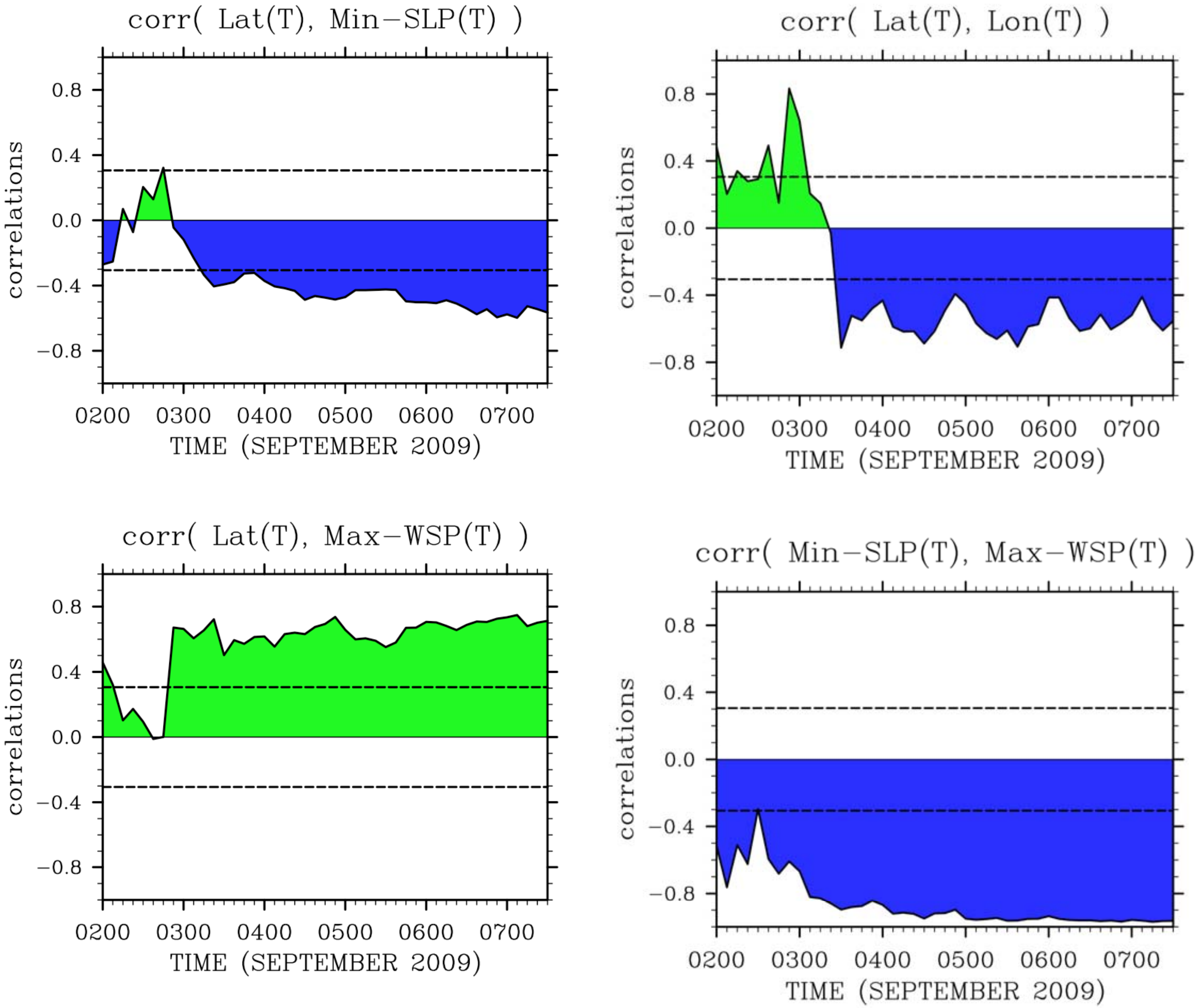


Mem26d2 300-850 mb Shear (m/s) @ t=1



Mem26d2 300-850 mb Shear (m/s) @ t=5




corr(Lat(T), Min−SLP(T))
corr(Lat(T), Lon(T))
corr(Lat(T), Max−WSP(T))
corr(Min−SLP(T), Max−WSP(T))
correlations
0.8
0.4
0.0
−0.4
−0.8
0200
0300
0400
0500
0600
0700
TIME (SEPTEMBER 2009)

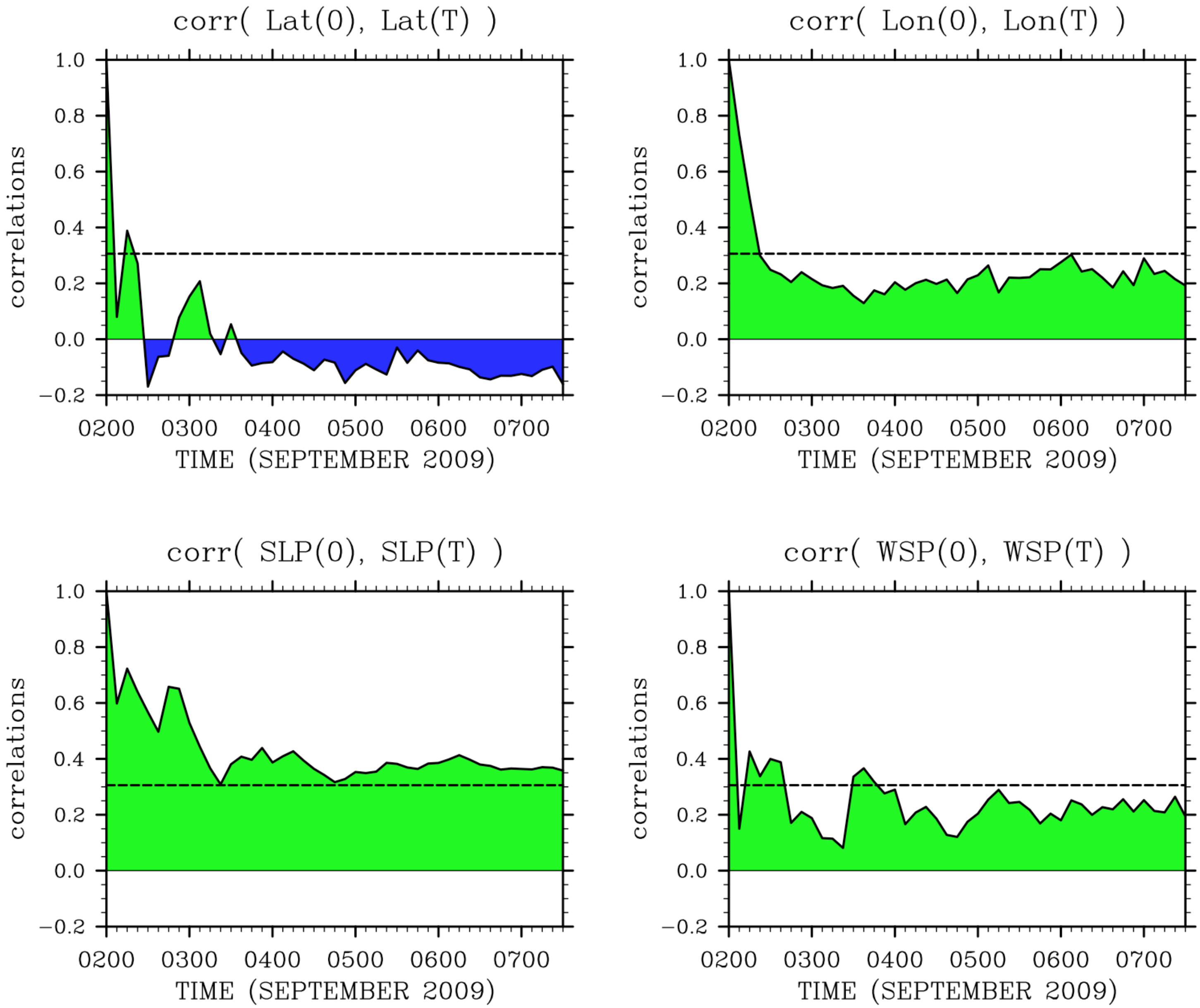


Figure 4 Time changes of correlation coefficients between initial time step and all time steps for the track (latitude, longitude) and the intensity (minimum sea level pressure and maximum wind speed) of Tropical Storm Erika

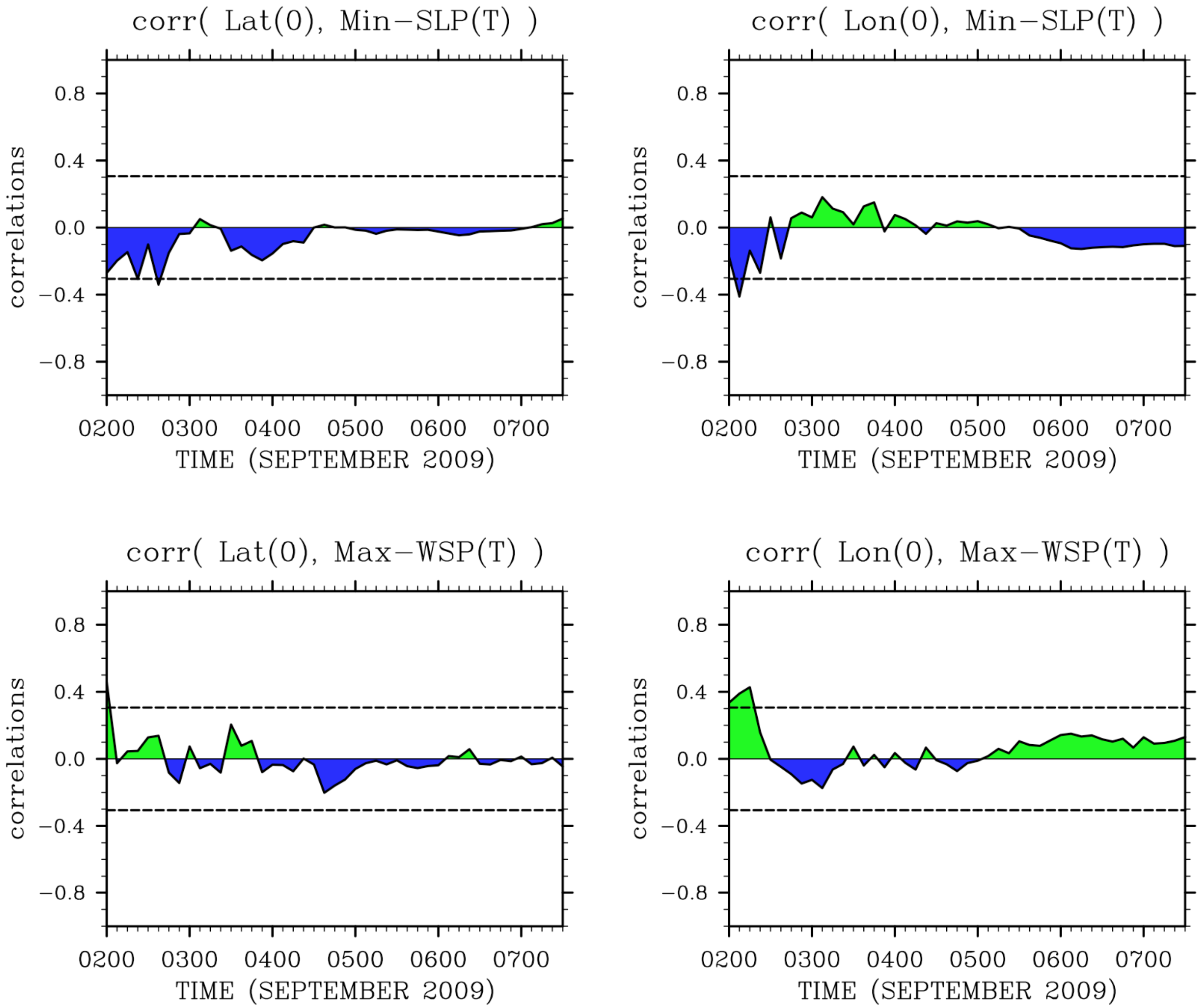


Figure 5 Time changes of correlation coefficients between the track (latitude, longitude) at initial time step and the intensity (minimum sea level pressure and maximum wind speed) at all time steps of Tropical Storm Erika