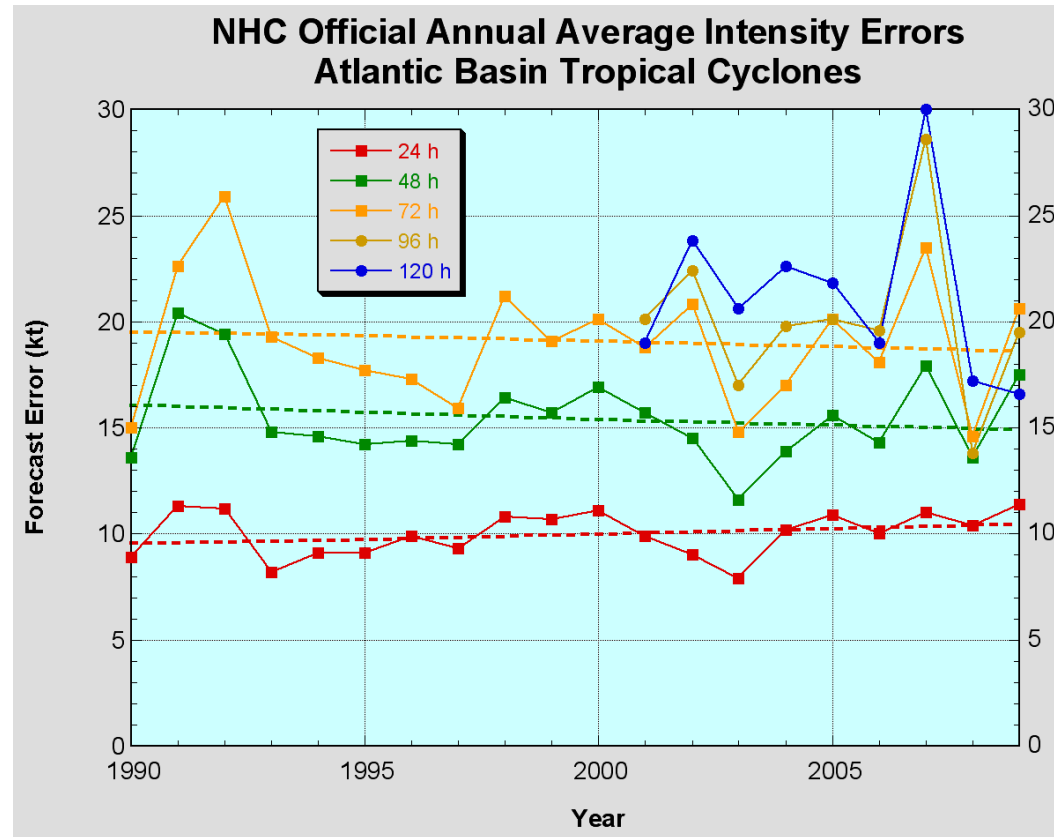
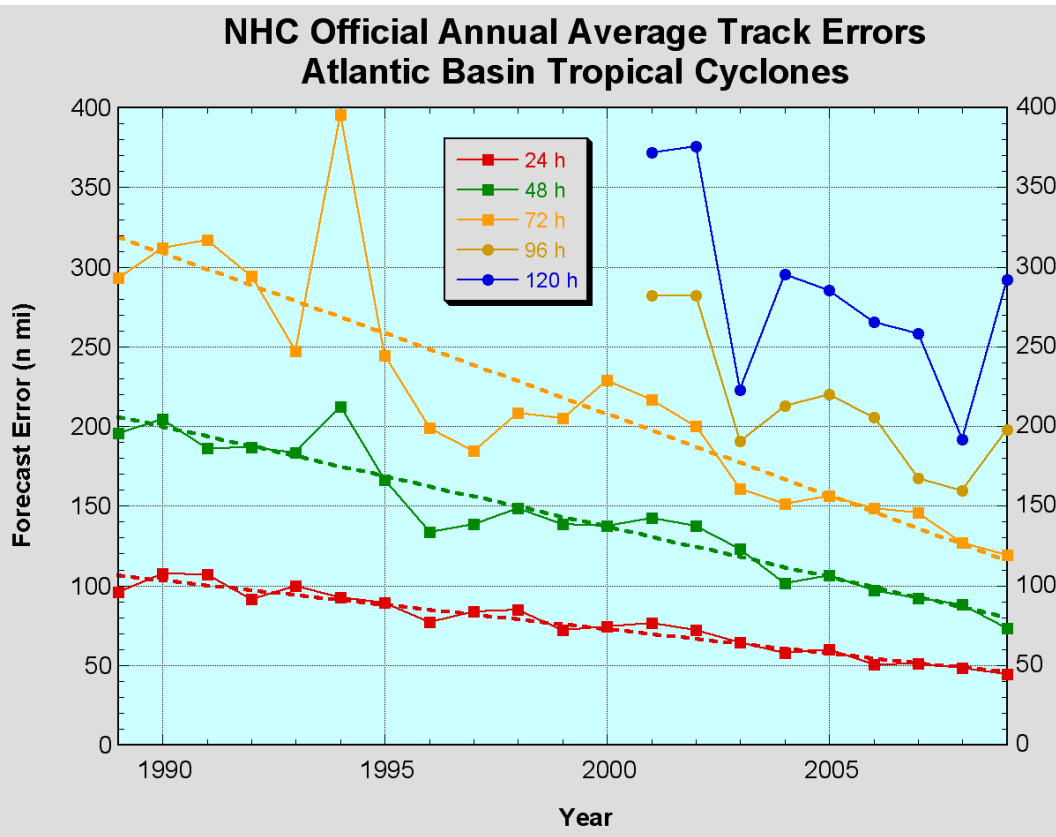


The Use of GPS Radio Occultation Data for Tropical Cyclone Prediction

Bill Kuo and Hui Liu
UCAR



Current capability of the National Hurricane Center

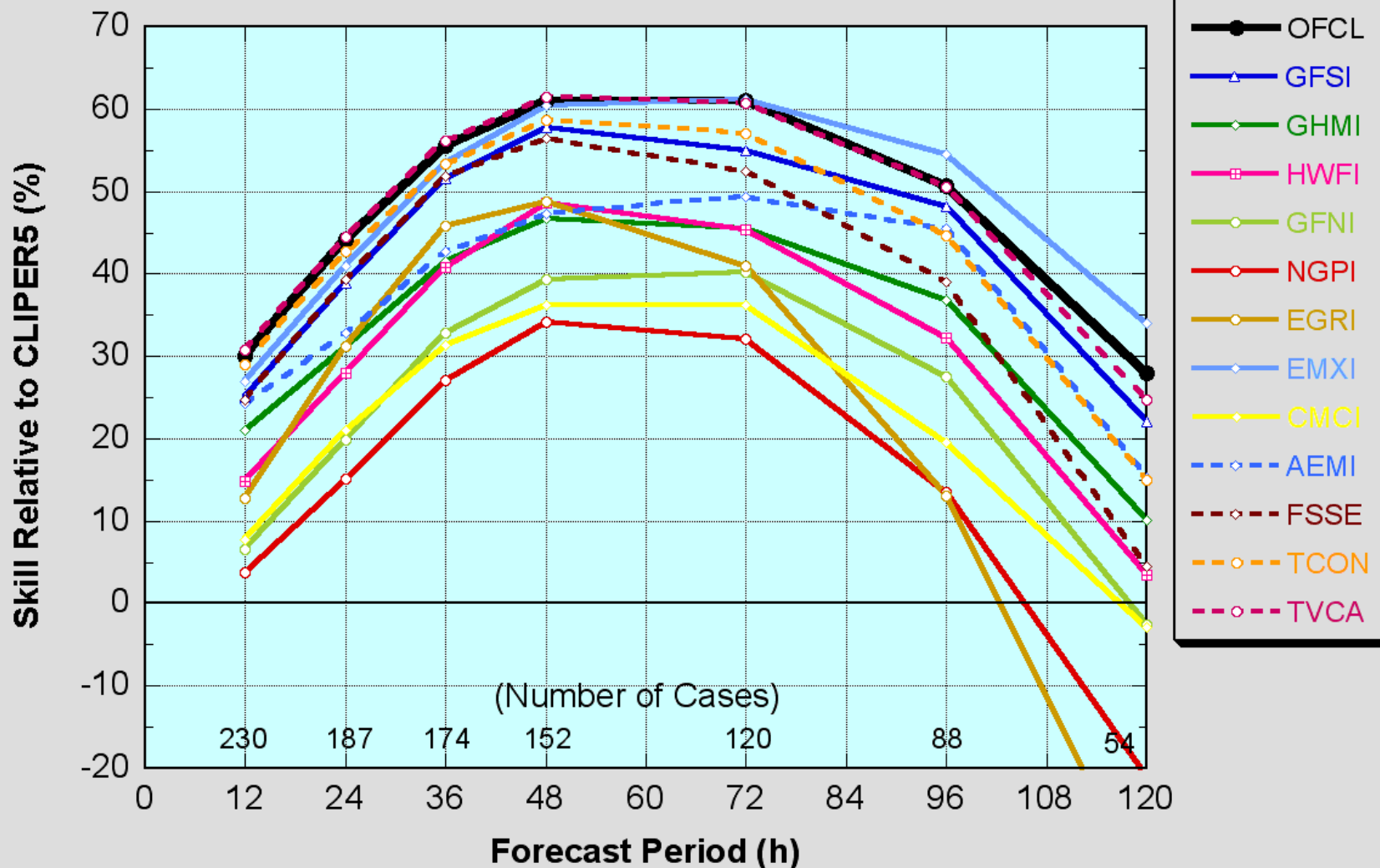


Good track forecast improvements. Errors cut in half in 15 years. Skill of 48h forecast as good as 24-h forecast 10 years ago.

No improvement in intensity forecast. Off by 2 categories 5-10% of the time.

2011 Preliminary NHC Verifications

**Track Forecast Skill (Operational Early Models)
2011 - Atlantic Basin**



ECMWF and GFS did well (again).

ECMWF beat consensus at longer ranges.

TVCA beat FSSE.

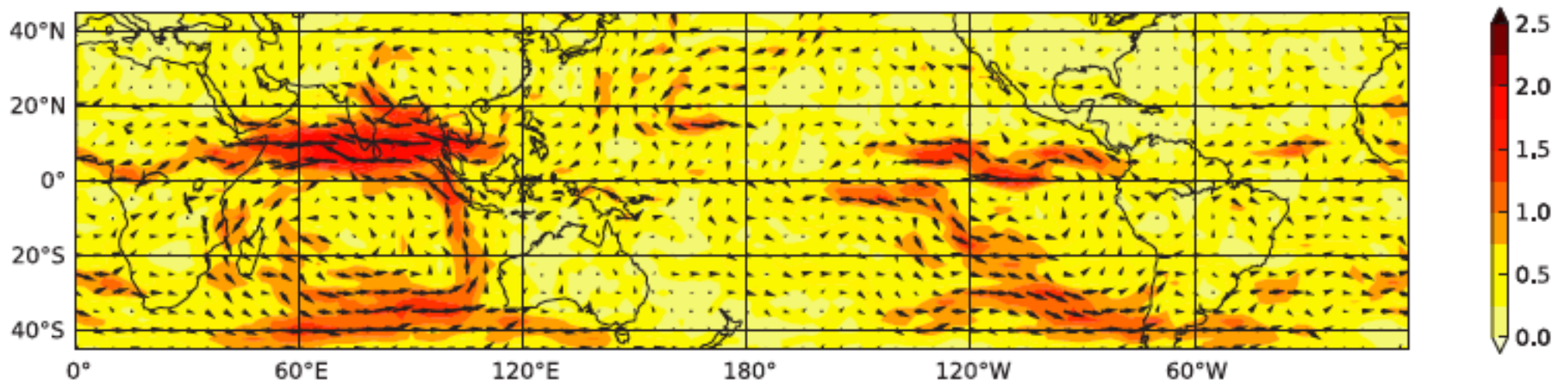
AEMI not as good as GFSI, even at 5 days.

GFDL and HWRF middle of the pack.

NGPS, CMC, UKMET trailed.

NOAA Hurricane Forecast Improvement Project (HFIP)

- 10-Year Goals:
 - Reduce average track error by 50% for day 1 through 5
 - Reduce average intensity error by 50% for day 1 through 5
 - Increase the probability of detection (POD) for rapid intensity change to 90% at Day 1 decreasing linearly to 60% at day 5, and decrease the false alarm ratio (FAR) for rapid intensity change to 10% for day 1 increasing linearly to 30% at day 5. **The focus on rapid intensity change is the highest forecast challenge identified by the National Hurricane Center.**
 - **Extend the lead time for hurricane forecasts out to Day 7 (with accuracy of Day 5 forecasts in 2003).**
- 5-Year Goals:
 - Reduce track and intensity forecast errors by 20%



Differences between ECMWF and GFS/EnKF for 200 mb wind, averaged from 7/26 – 9/27, 2010. From Hamill et al (2011). Larger difference over Western Pacific is noted.

GPS RO observations advantages for weather analysis and prediction

- There are considerable uncertainties in global analyses over data void regions (e.g., where there are few or no radiosondes), despite the fact that most global analyses now make use of satellite observations.
- GPS RO missions (such as COSMIC) can be designed to have globally uniform distribution (not limited by oceans, or high topography).
- The accuracy of GPS RO is compatible or better than radiosonde, and can be used to calibrate other observing systems.
- GPS RO observations are of high vertical resolution and high accuracy.
- GPS RO is an active sensor, and provides information that other satellite observing systems could not provide
- GPS RO provide valuable information on the 3D distribution of moisture over the tropics, which is important for typhoon prediction.

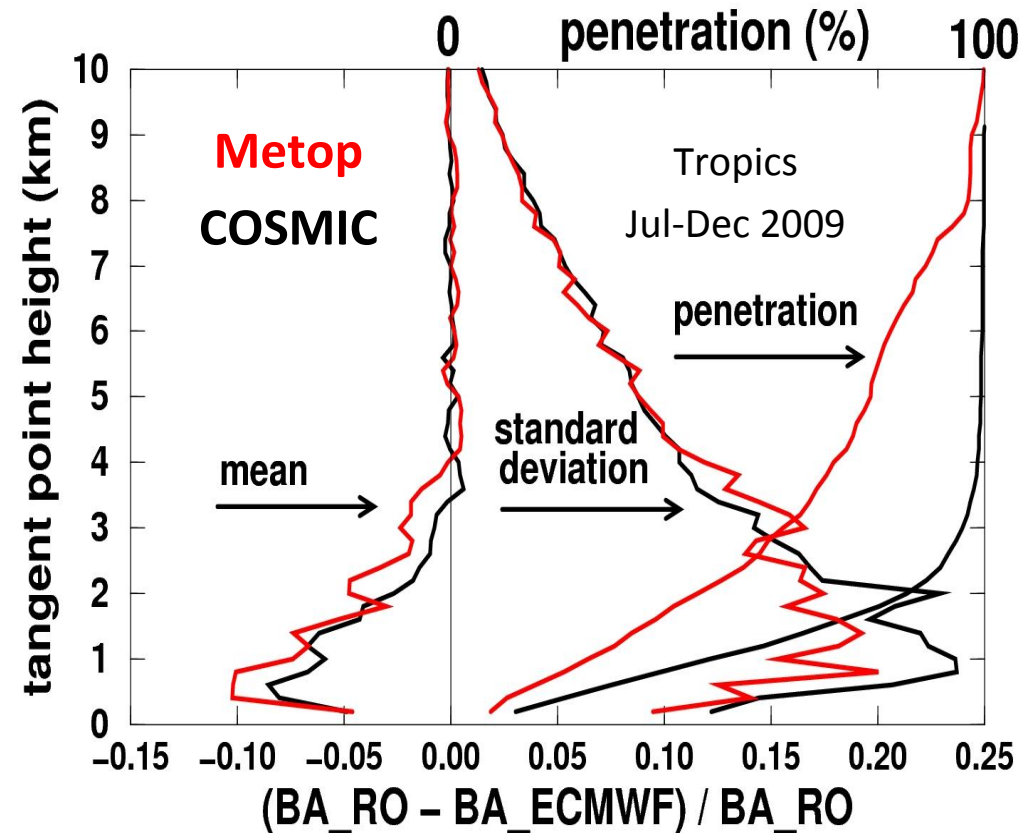
Challenges for Tropical Cyclone Prediction

- Some of the current GPS RO missions do not provide much data in the lower troposphere.
- There are still significant uncertainties and challenges for GPS RO to provide accurate measurement in the lowest 2 km of the tropical troposphere.
- How would this impact tropical cyclone prediction?

COSMIC and Metop/GRAS Comparisons With ECMWF

- Tropics, Jul-Dec 2009
- Metop/GRAS processed down to first data gap
- **Metop/GRAS profiles have worse penetration than COSMIC**
- **Metop/GRAS BA's negatively biased by several percent in lower troposphere**

Metop/COSMIC Bending Angles



Courtesy of Bill Schreiner



Hurricane Ernesto:

Formed: 25 August 2006

Reached Hurricane strength: 27 August

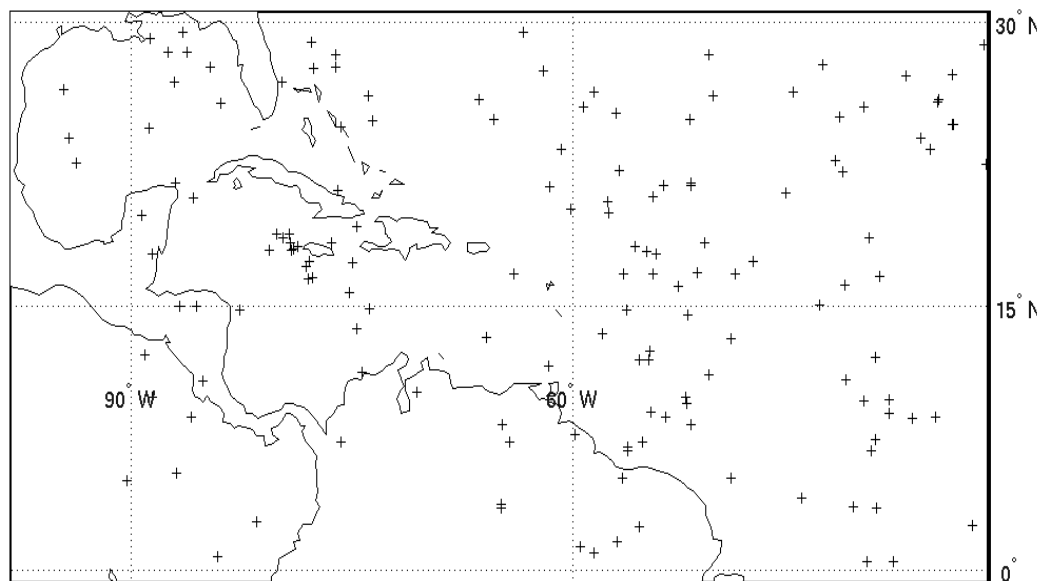
Dissipated: 1 September 2006

15:50 UTC 27 August 2006

Picture taken by MODIS, 250 m resolution

WRF/DART ensemble assimilation of COSMIC GPSRO soundings

- WRF/DART ensemble Kalman filter data assimilation system
- 36-km, 32-members, 5-day assimilation
- Assimilation of 178 COSMIC GPSRO soundings (with nonlocal obs operator, Sokolovskiy et al) plus satellite cloud-drift winds
- Independent verification by ~100 dropsondes.



178 COSMIC GPSRO
soundings during 21-
26 August 2006

From Liu et al. (2011)

Experiment Design

Name	Conventional data	GPS RO	
NODA	No	No	Continuous forecast
ONLY	No	Yes	GPS only
ONLY6km	No	Yes above 6 km	GPS only above 6 km
ONLY2km	No	Yes above 2 km	GPS only above 2 km
CTRL	Yes	No	Convectional
RO	Yes	Yes	Conventional + GPS
RO6km	Yes	Yes above 6 km	Convectional + GPS 6km
RO2km	Yes	Yes above 2 km	Convectional + GPS 2km

- > The first four experiments try to identify the impact of GPS data in a clean setting (without the use of any other data)
- > The second four experiments assess the impact of GPS RO data in a more realistic operational setting.
- > Conventional data includes radiosondes, surface, aircraft reports, satellite cloud track winds, no radiance.

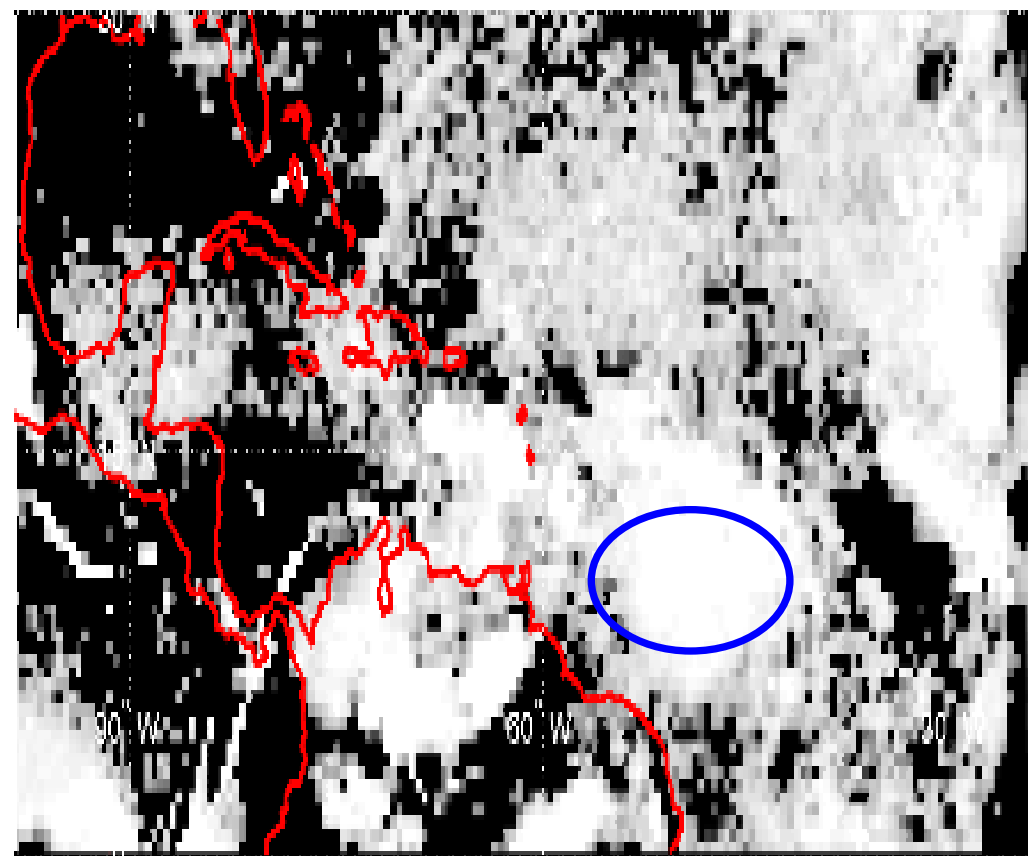
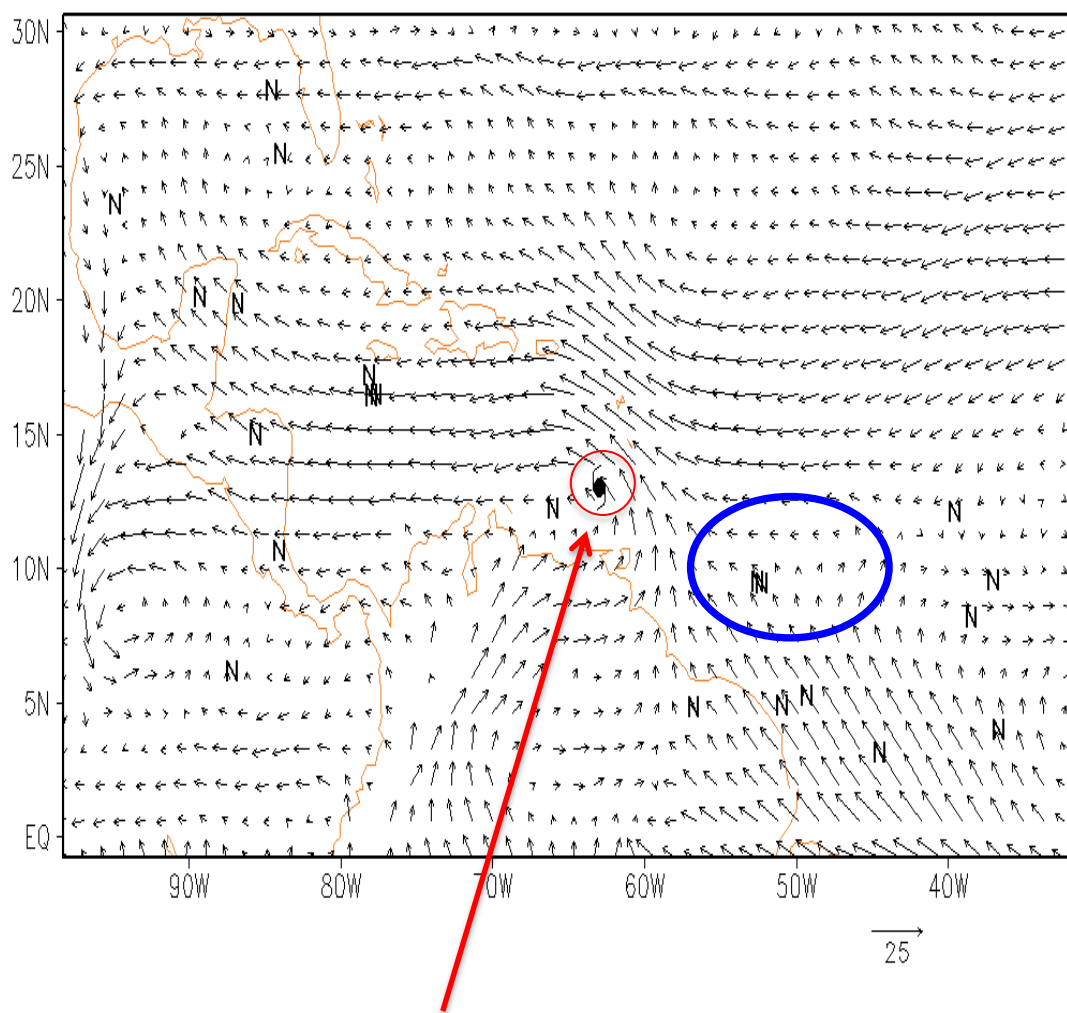
Experiment Design

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CTRL	Yes	No	Convectional
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- > The first four experiments try to identify the impact of GPS data in a clean setting (without the use of any other data)
- > The second four experiments assess the impact of GPS RO data in a more realistic operational setting.
- > Conventional data includes radiosondes, surface, aircraft reports, satellite cloud track winds, no radiance.

Analysis of 850 hPa Wind and Total Column Cloud Water (06Z August 23, 36 hours before Ernesto's genesis, GPSONly run)

GPS RO locations and wind 850 hPa

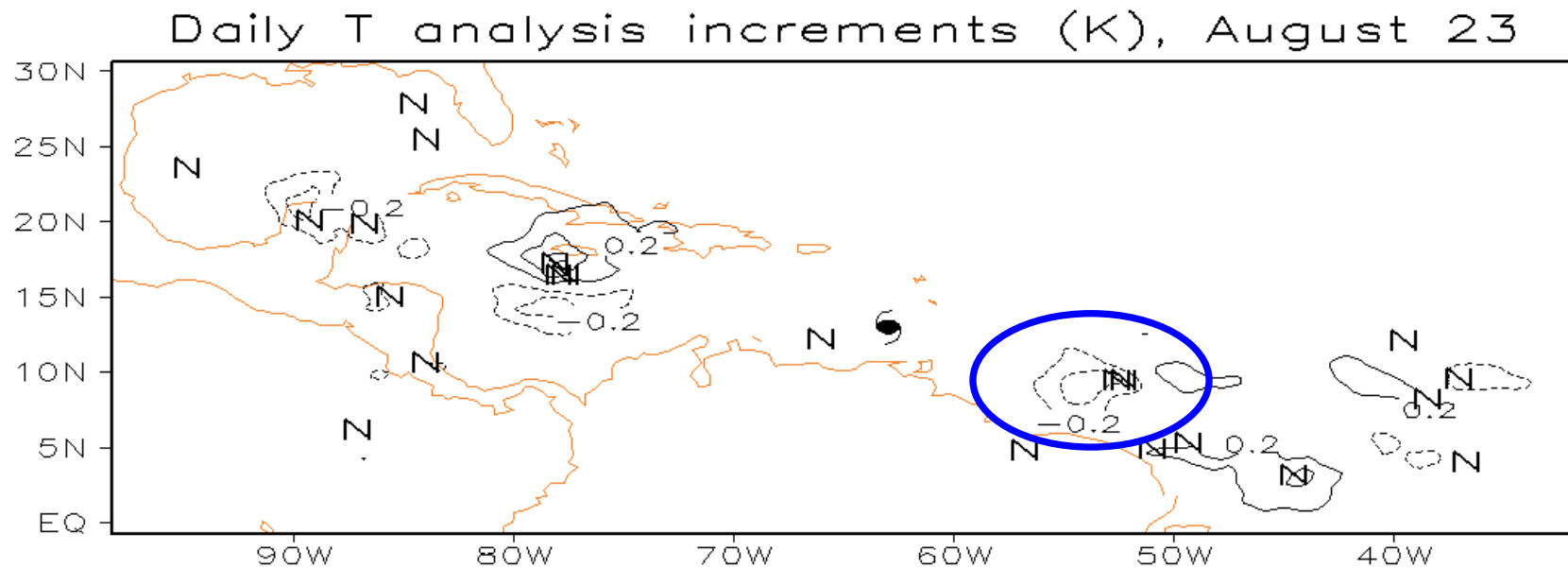
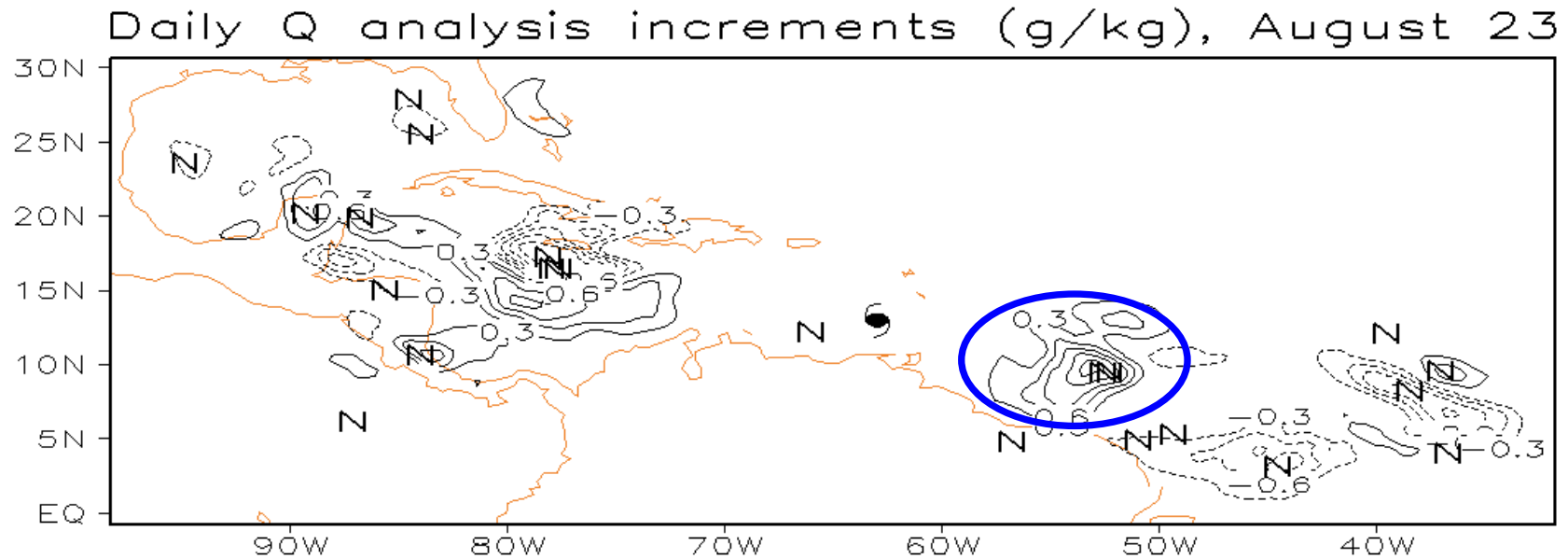


Where Ernesto formed at 0000
UTC 25 August

Convergence and convection in Ernesto's genesis area.

Analysis Increments of Q and T (GPSonly run)

(850 hPa, August 23, 2 days before Ernesto's genesis)



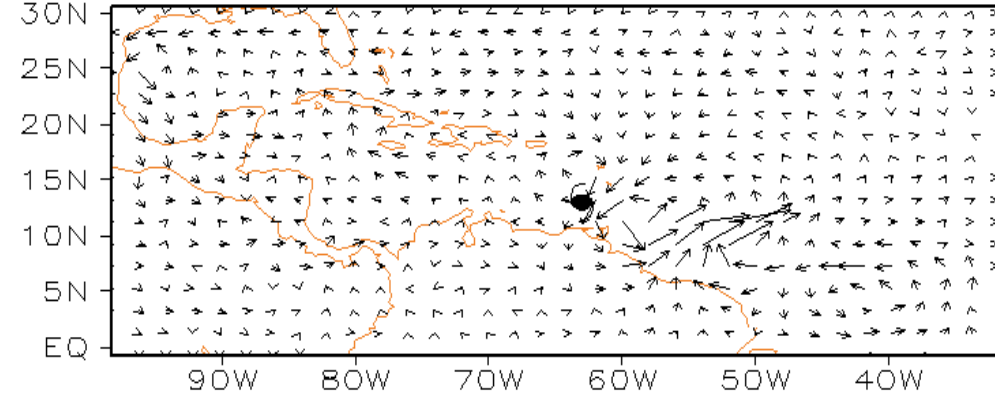
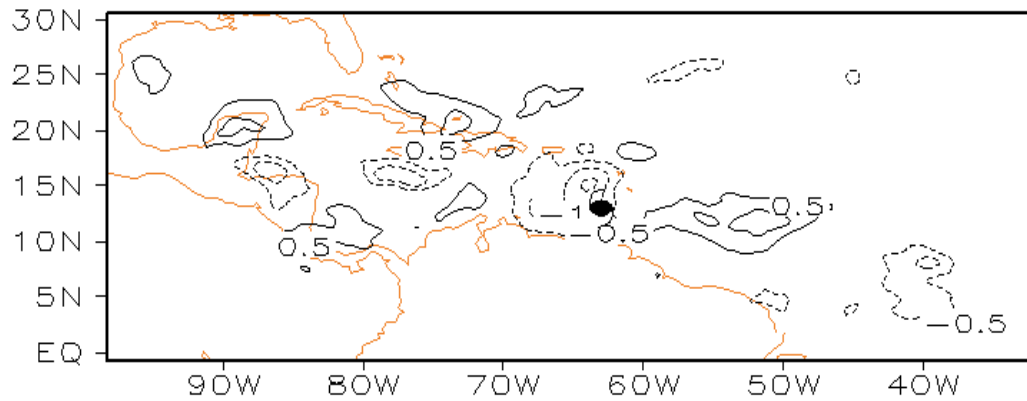
Temperature increment is small; Water vapor increment is large.

2-hour Forecast Difference of GPSONly-NODA (700 hPa)

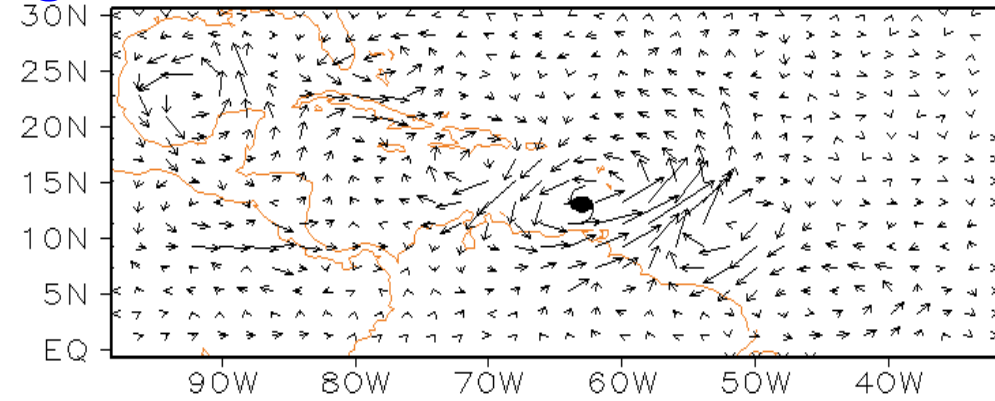
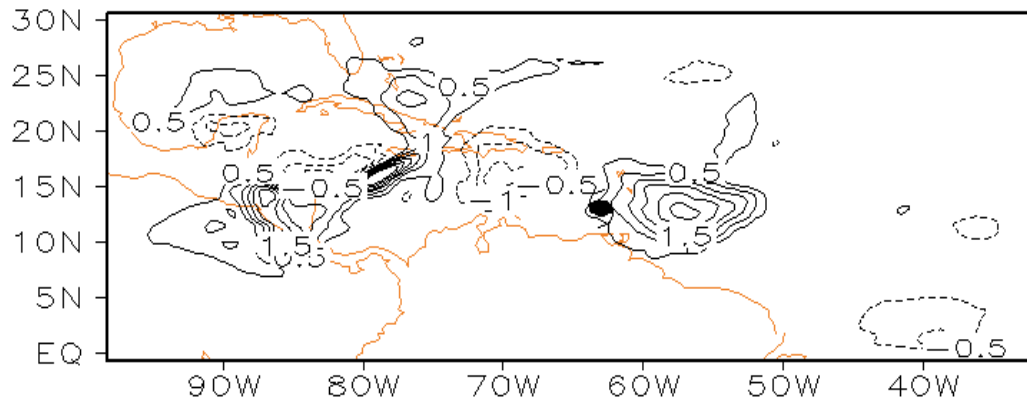
Water vapor

06Z 23 August

Wind

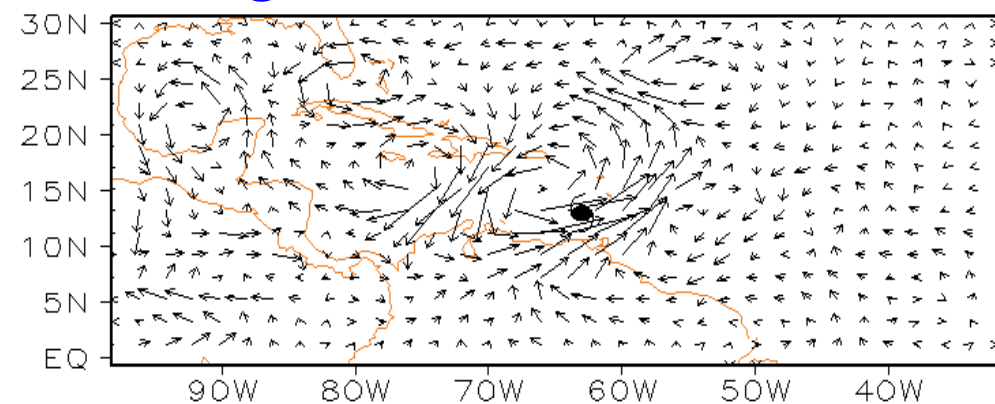
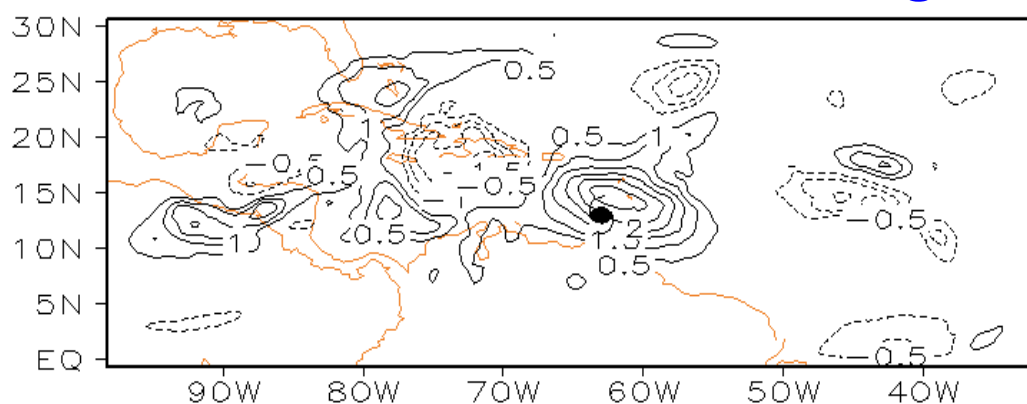


00Z 24 August

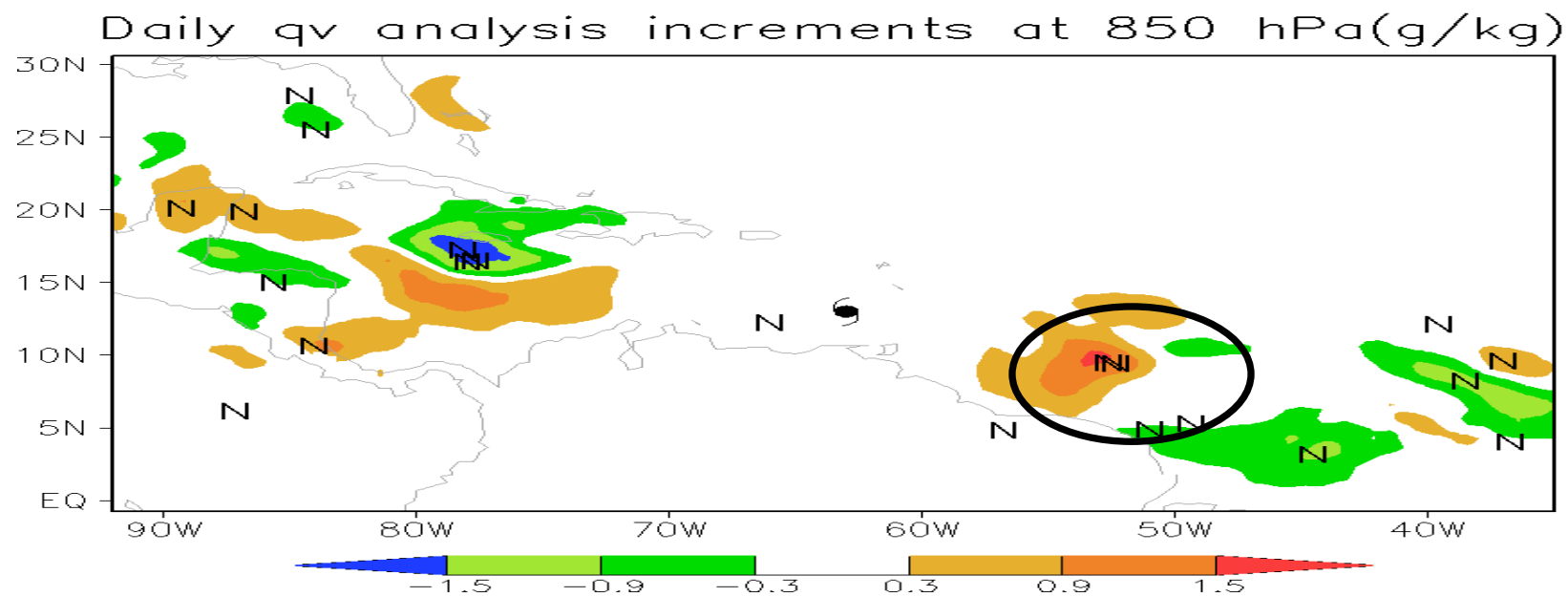
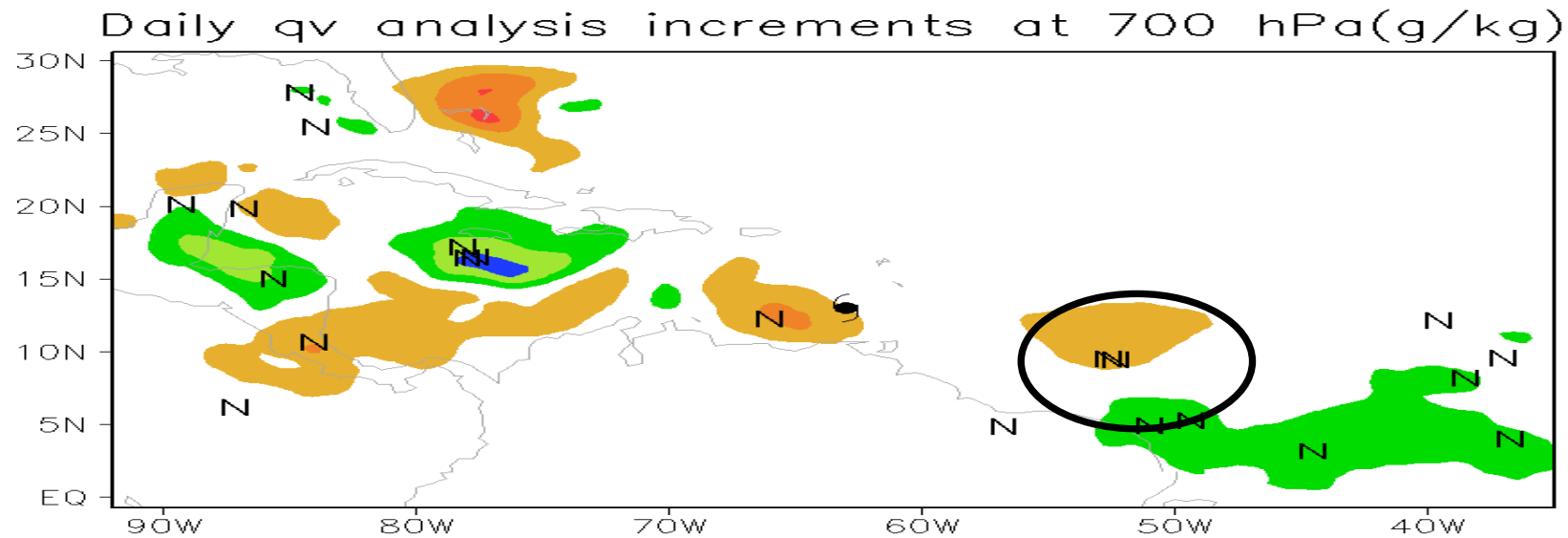


00Z 25 August

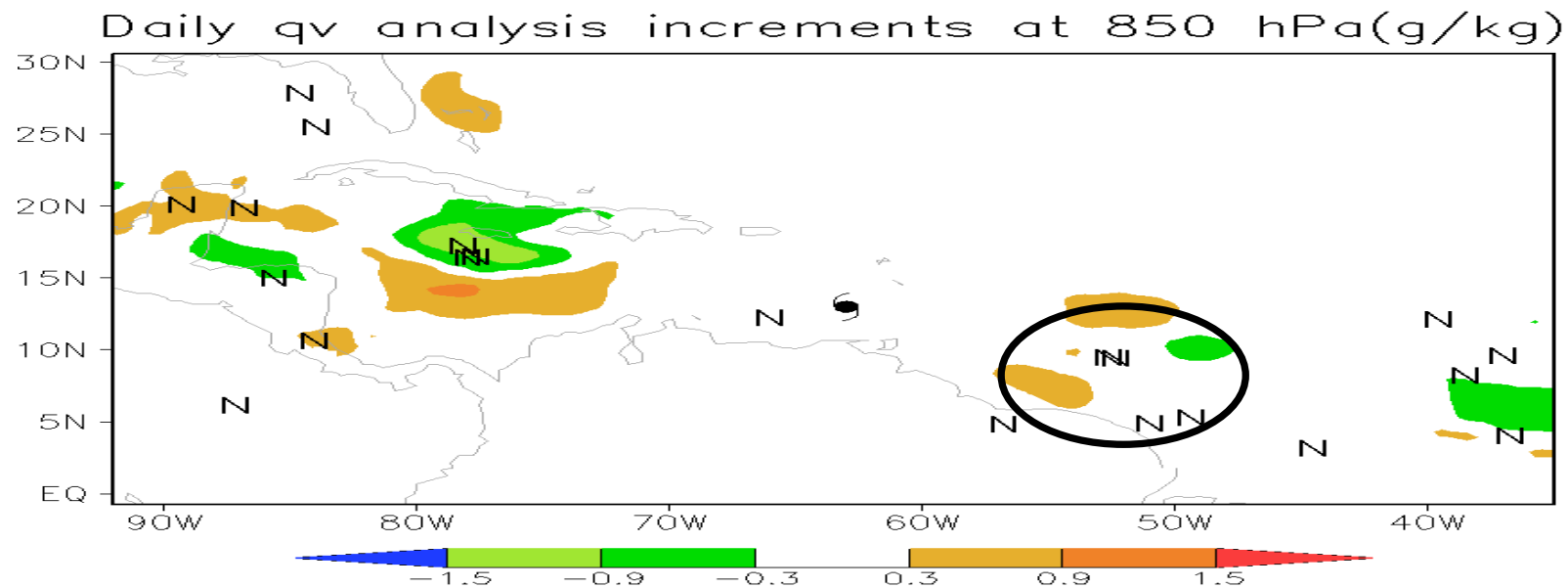
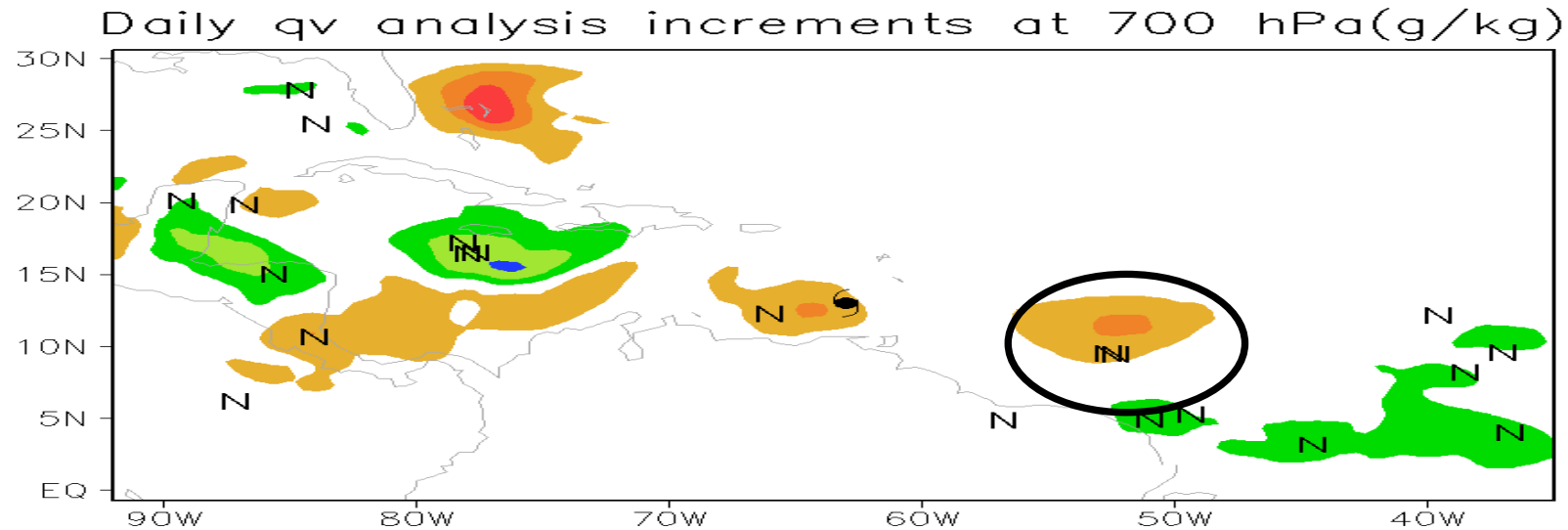
Ernesto's genesis time



Analysis Increments of Q (Only run)
(850 hPa, 06Z August 23, 2 days before Ernesto's genesis)

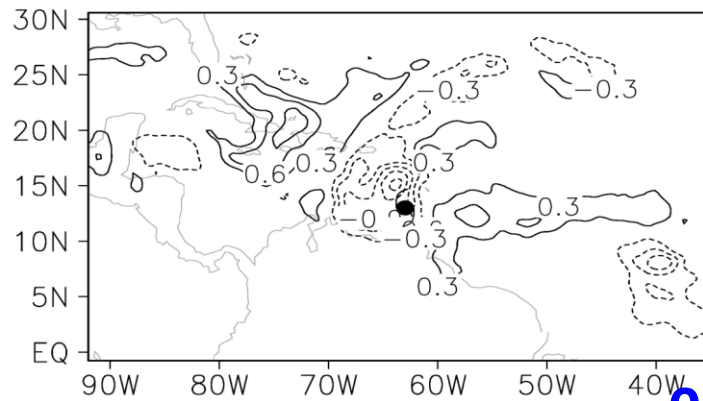


Analysis Increments of Q (Only2km run)
(850 hPa, 06Z August 23, 2 days before Ernesto's genesis)

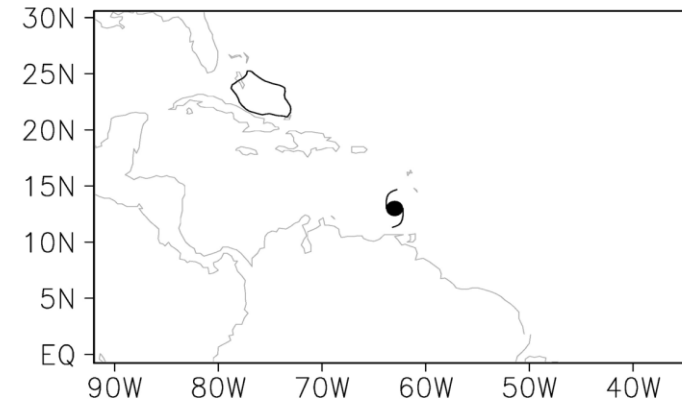


2-hour Water Vapor Differences (700 hPa)

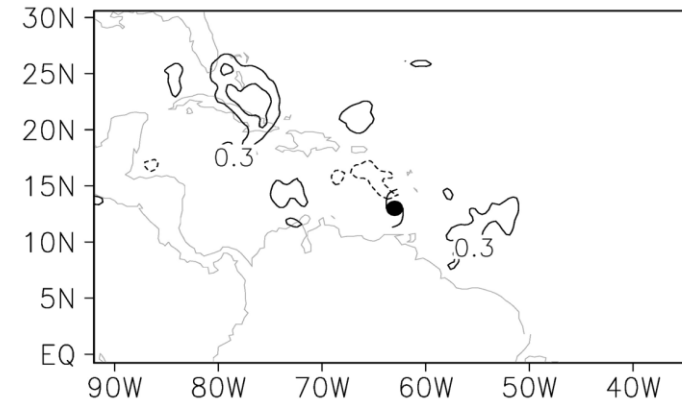
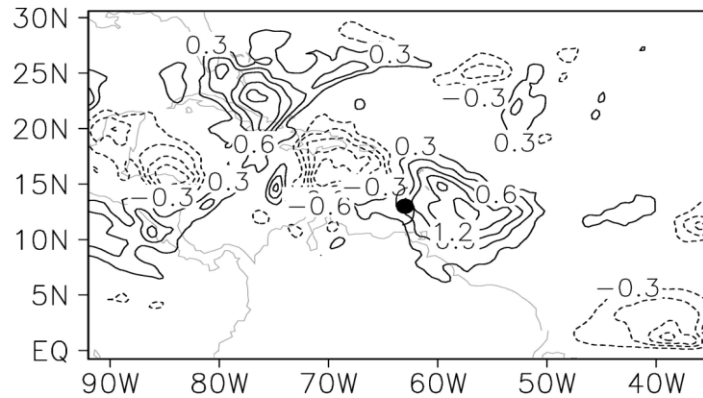
Only - NODA 06Z 23 August



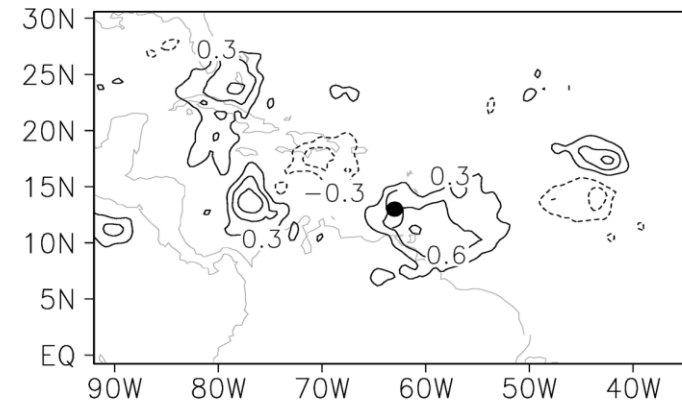
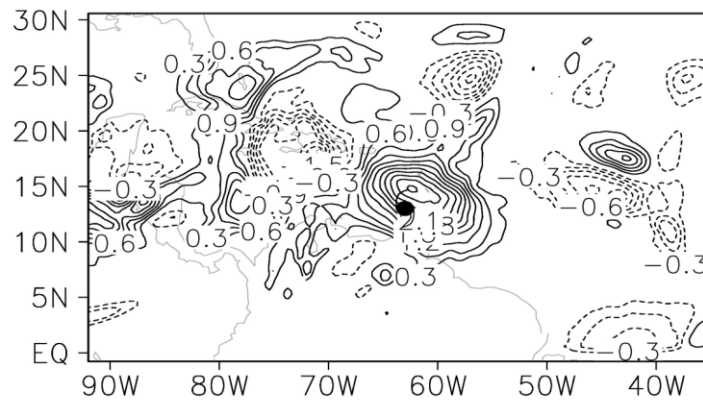
Only6km - NODA



00Z 24 August



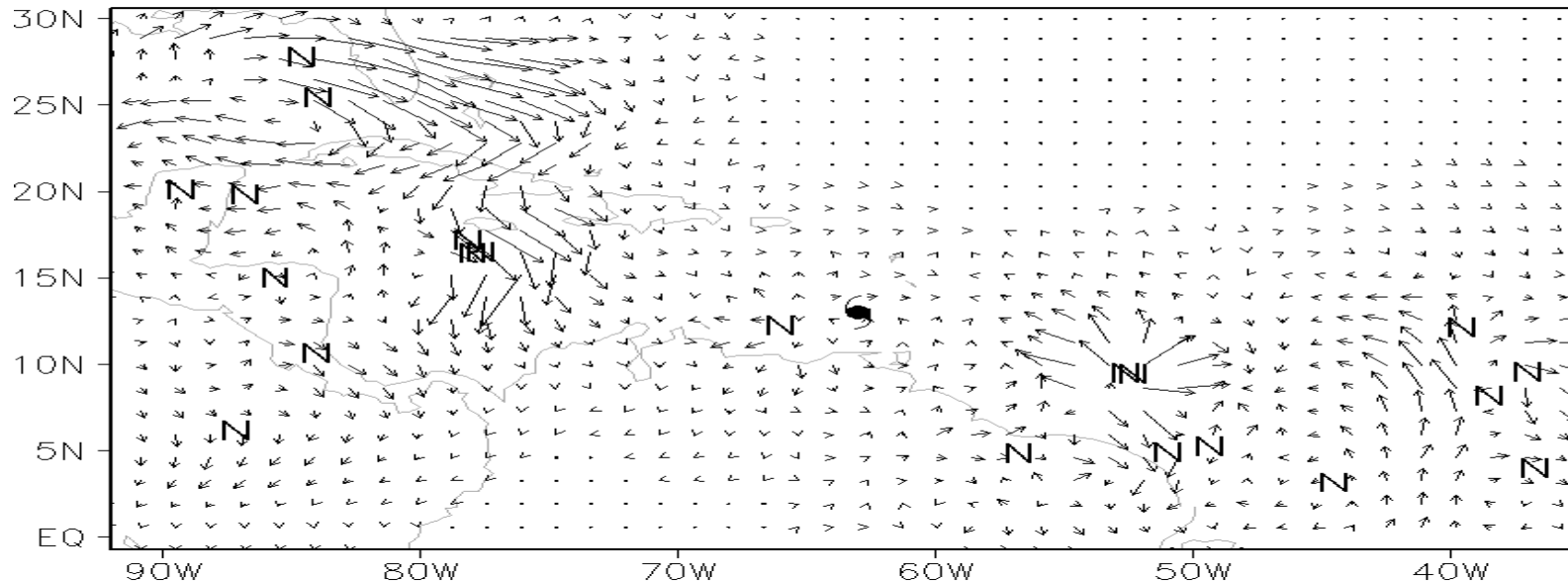
00Z 25 August Ernesto's genesis time



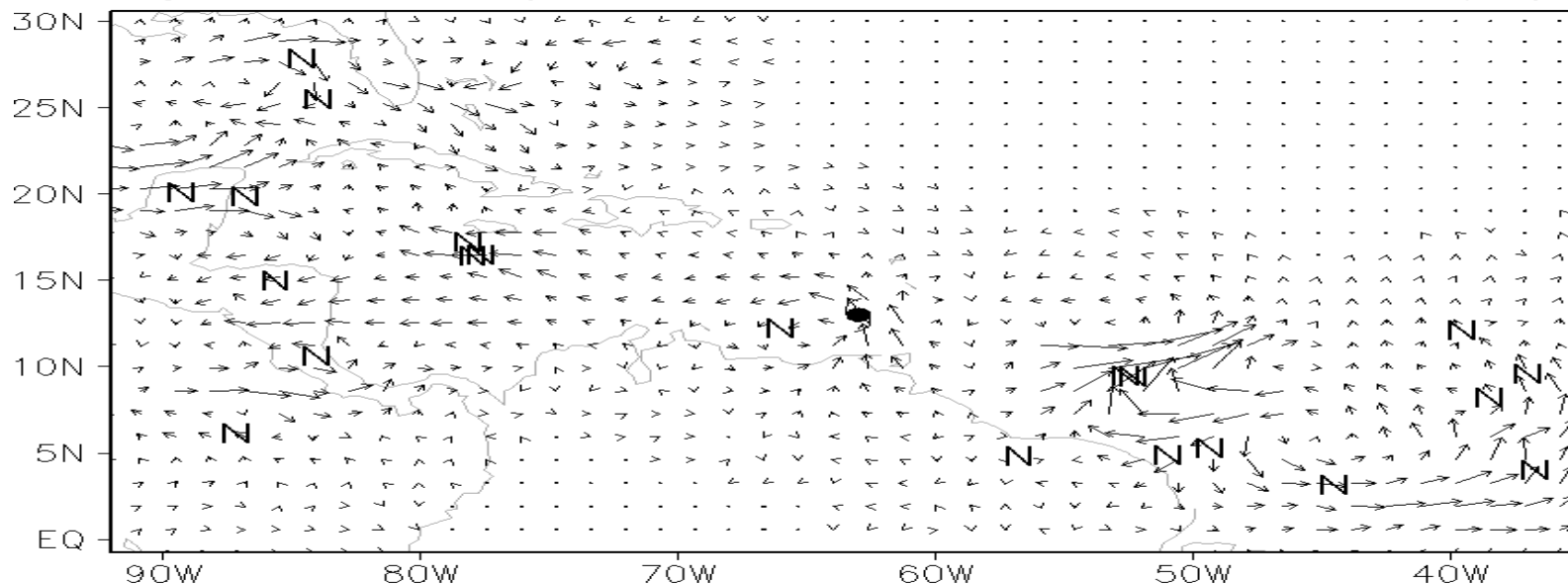
Analysis Increments of Wind (Only run)

(August 23, 2 days before Ernesto's genesis, m/s)

Daily wind analysis increments at 250 hPa (m/s)



Daily wind analysis increments at 700 hPa (m/s)

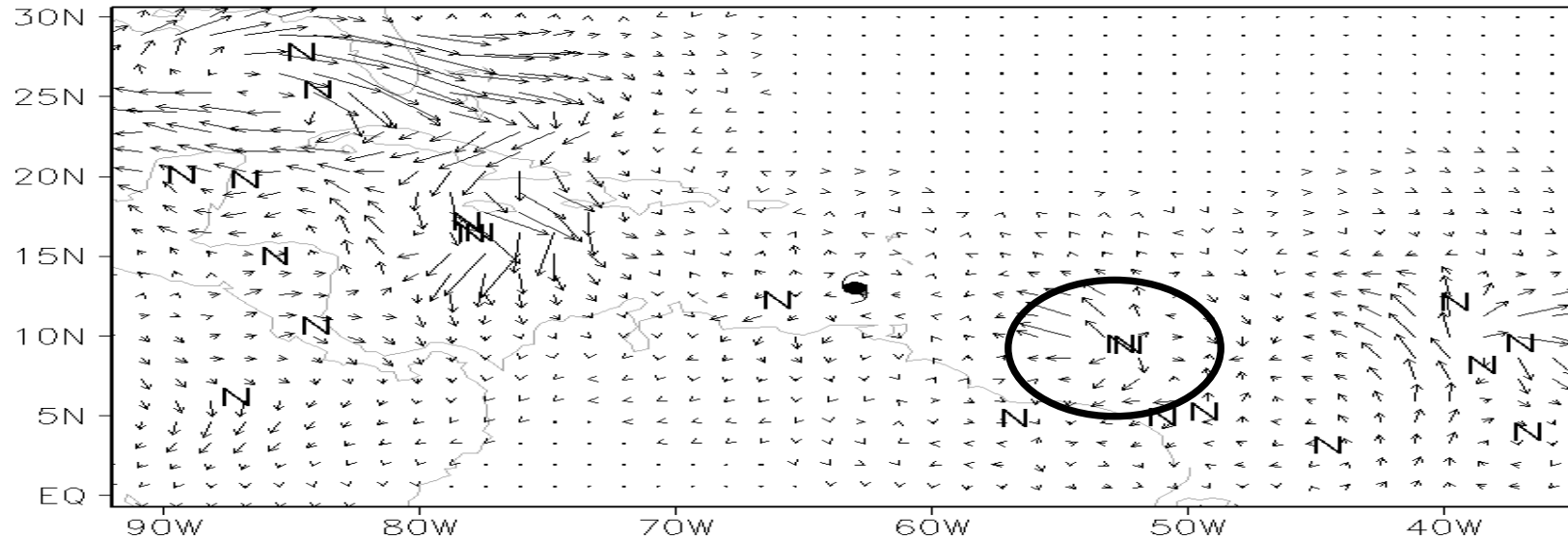


Strong correlation between GPS RO data in the lower troposphere and winds at all levels.

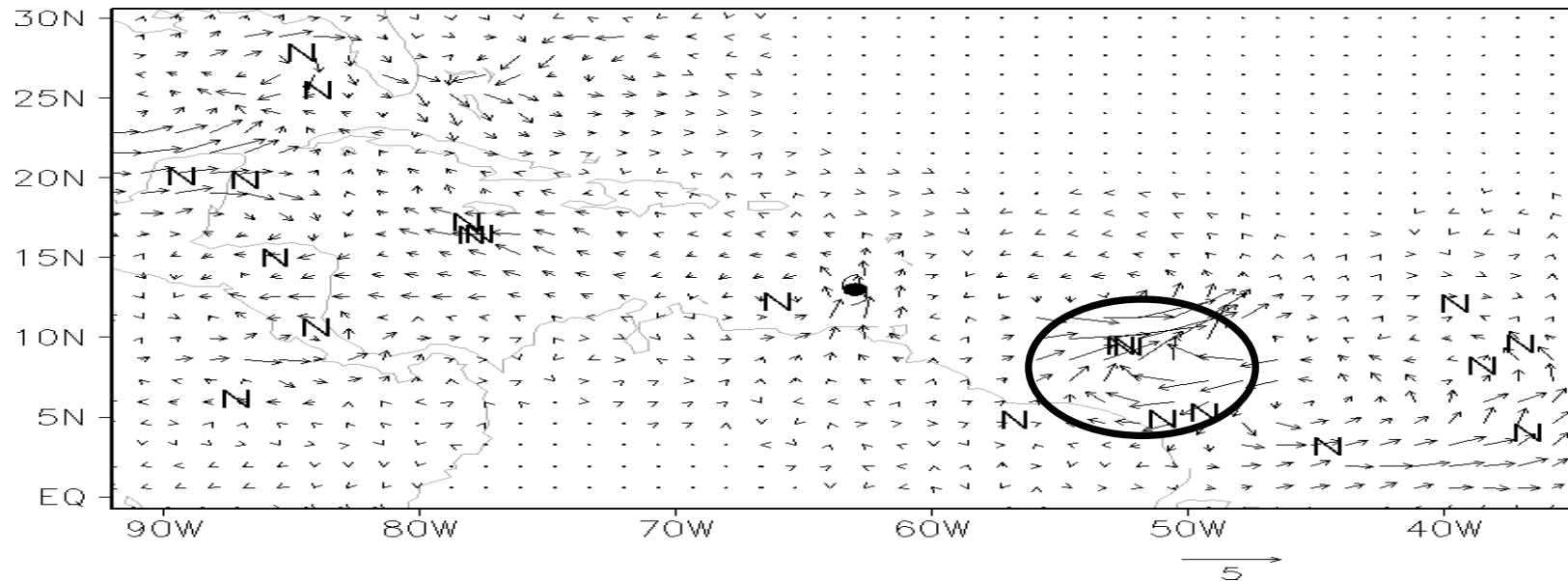
Analysis Increments of Wind (Only2km run)

(August 23, 2 days before Ernesto's genesis, m/s)

Daily wind analysis increments at 250 hPa (m/s)

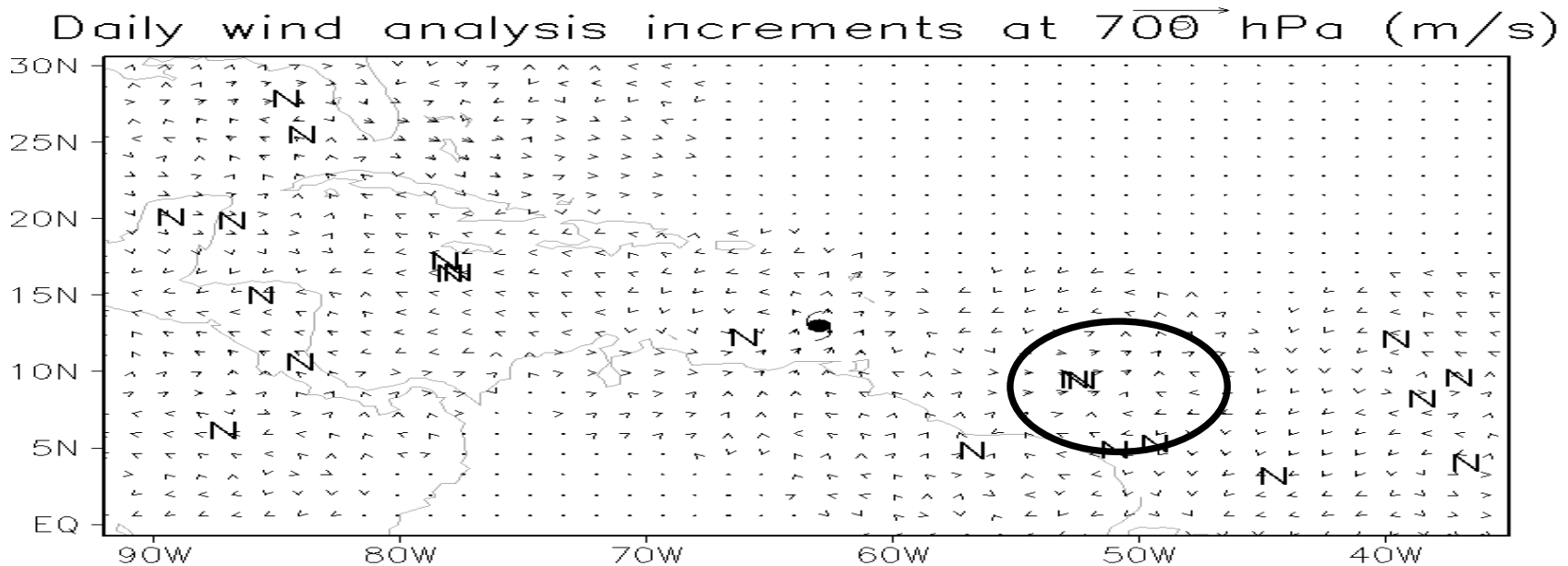
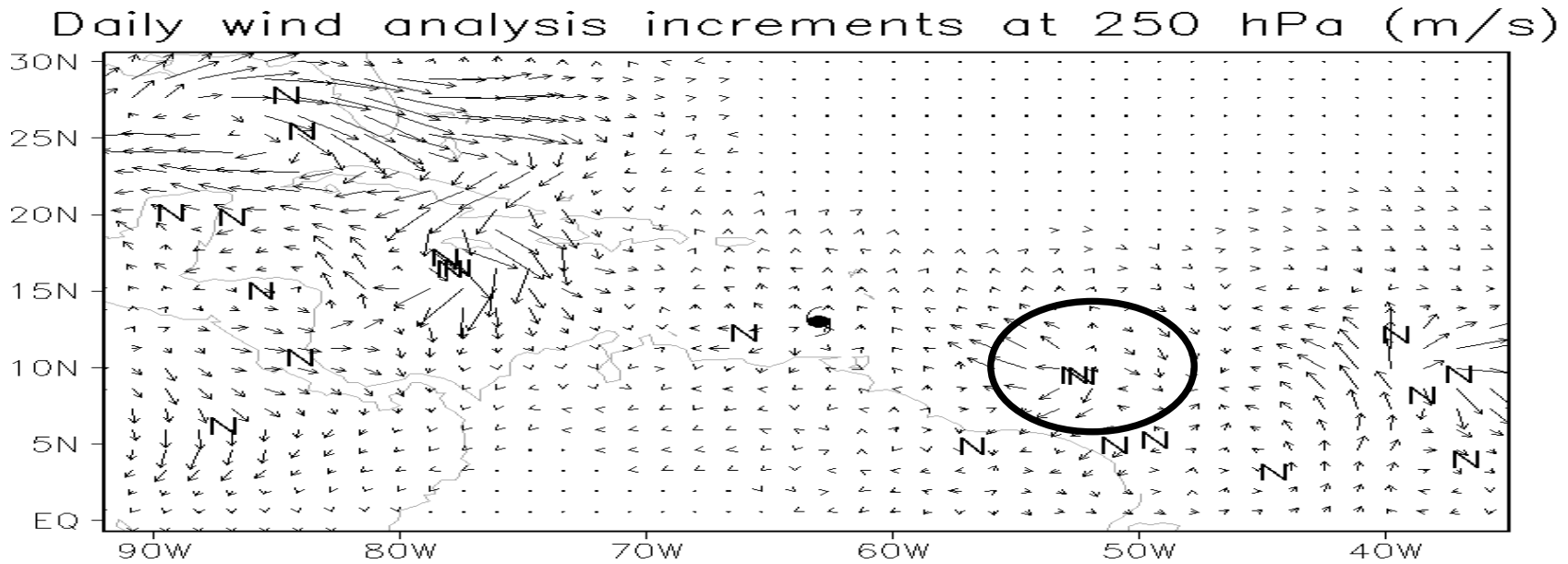


Daily wind analysis increments at 700 hPa (m/s)



Analysis Increments of Wind (Only 6km run)

(August 23, 2 days before Ernesto's genesis, m/s)

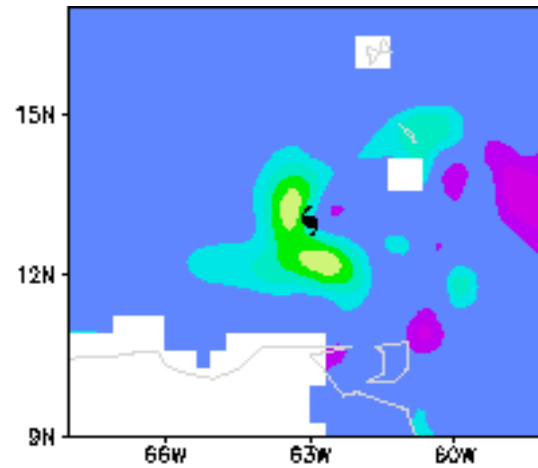
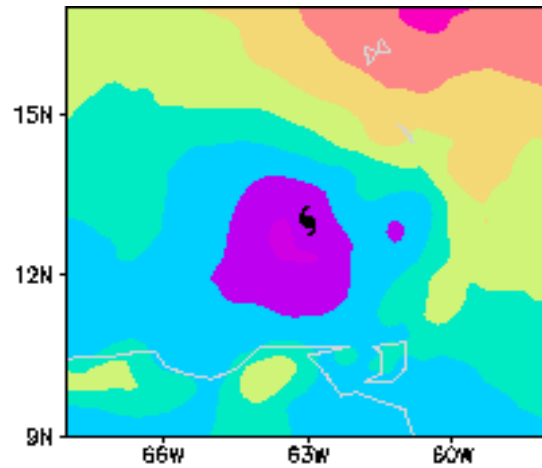


Strong

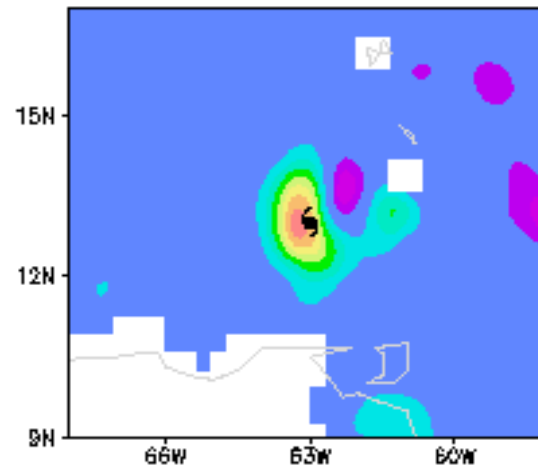
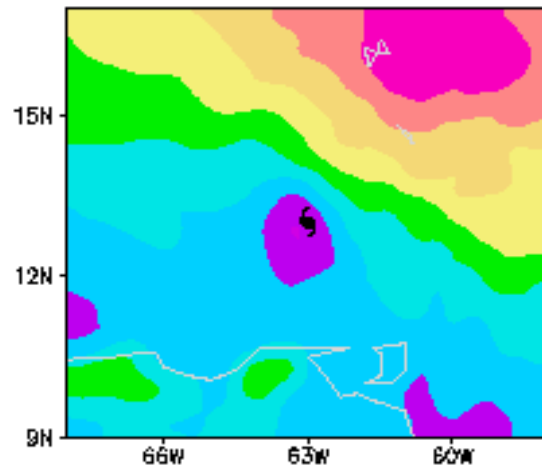
Assimilation Experiments of RO and Conventional Data

- CTRL (NO GPS) run: Assimilate conventional data.
 - RO6km run: Add RO refractivity data only higher than 6km
 - RO2km run: Add RO refractivity data only higher than 2km
 - RO run: Add RO refractivity data of all levels.
-
- Non-local RO refractivity operator is used.
 - Radiance is not assimilated in these experiments.

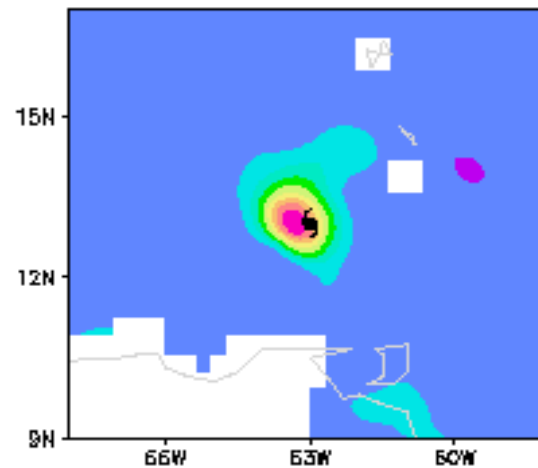
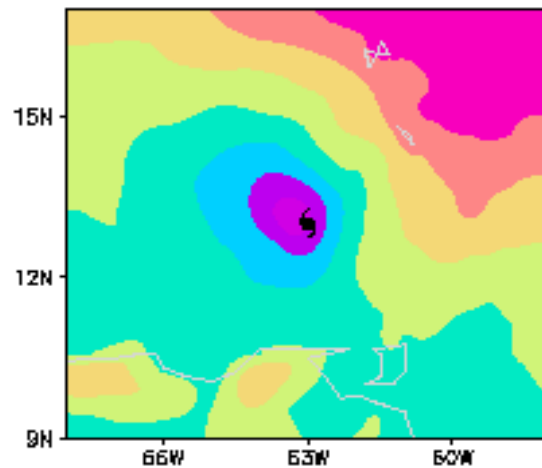
Analyses of SLP and 1000 hPa Vorticity (00UTC 25 August)



CTRL



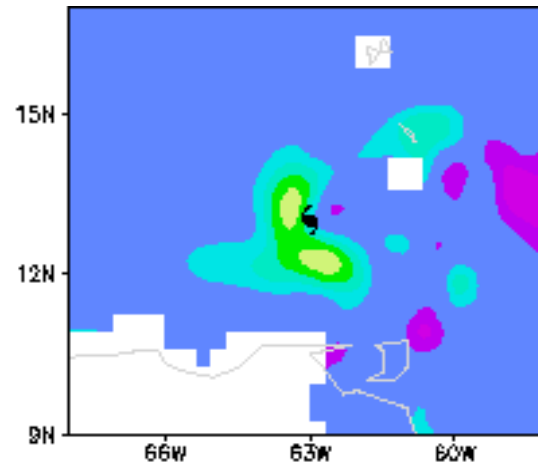
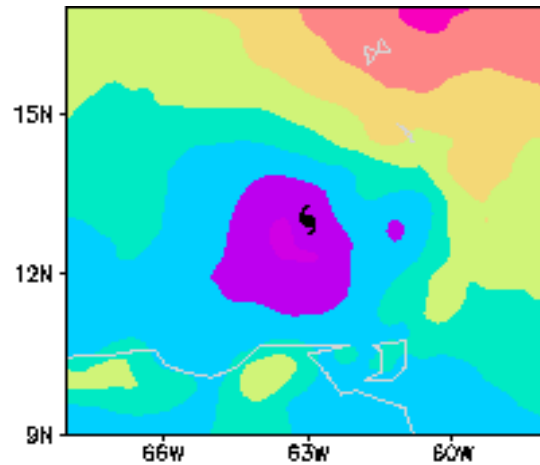
RO6km



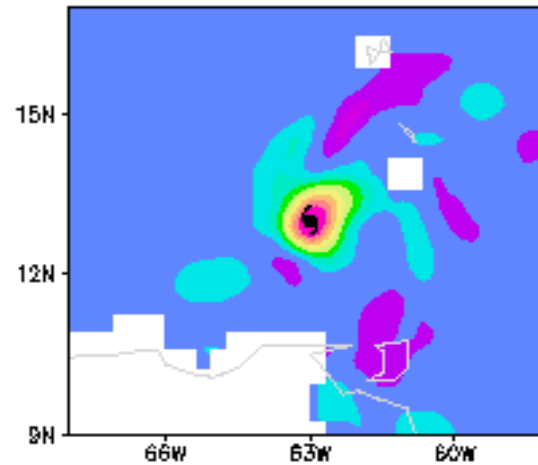
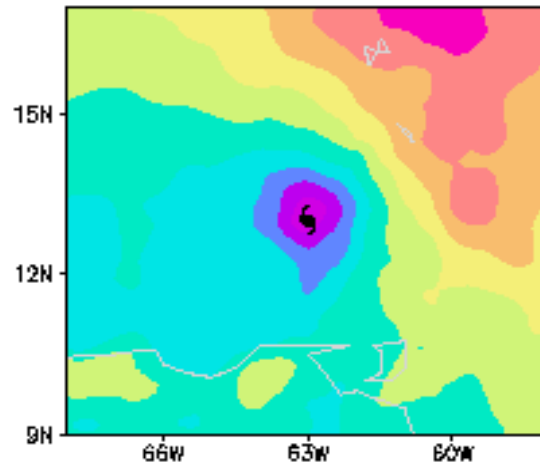
RO



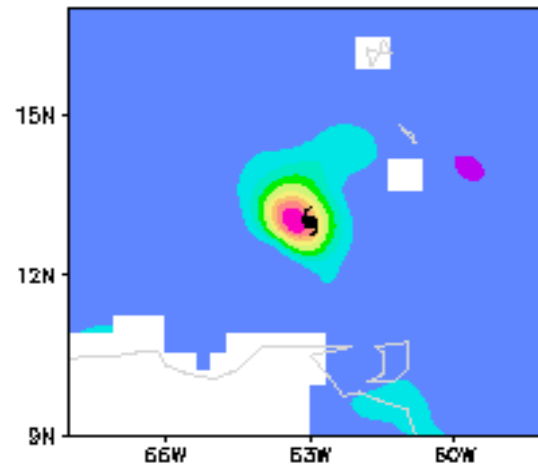
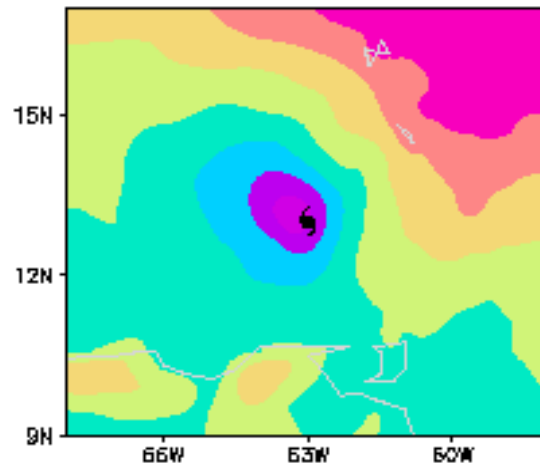
Analyses of SLP and 1000 hPa Vorticity (00UTC 25 August)



CTRL



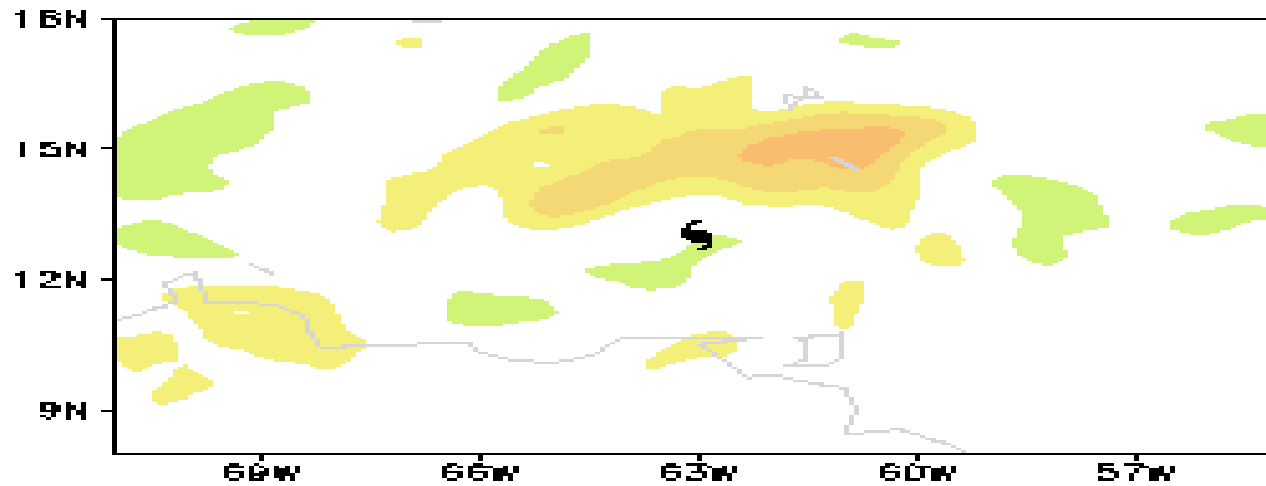
RO2km



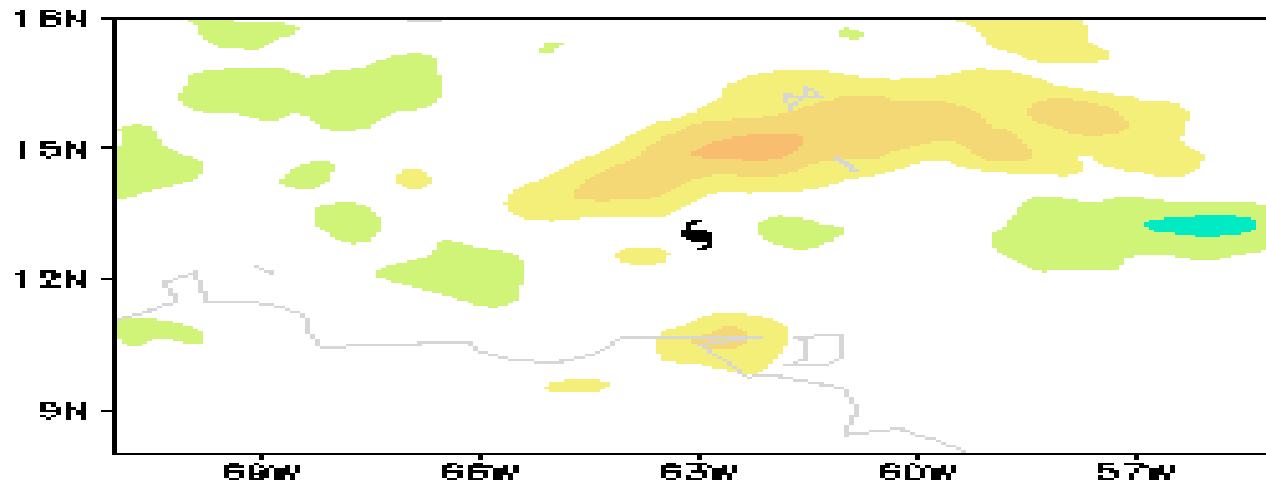
RO



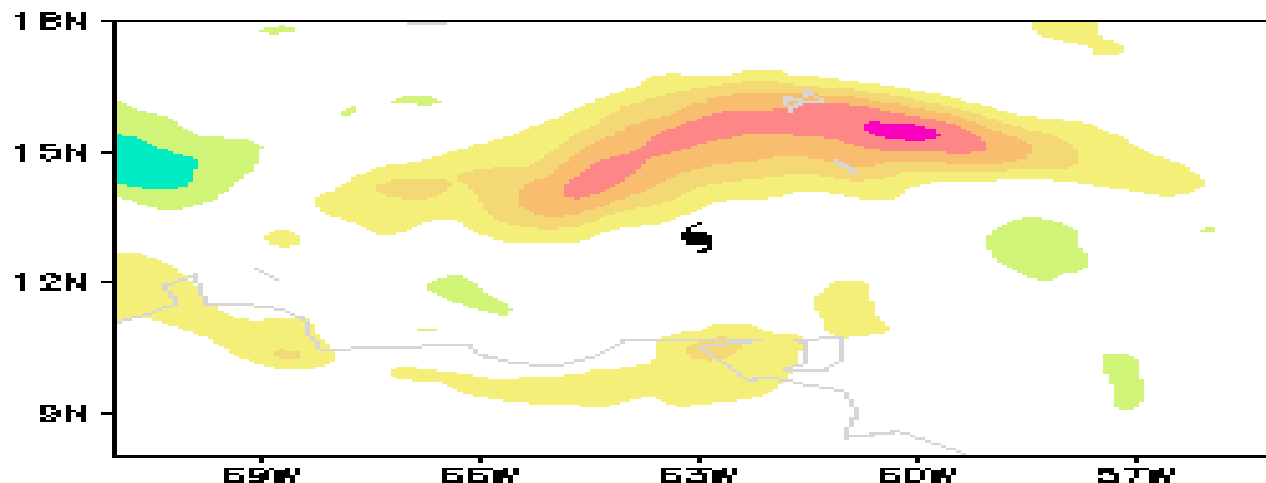
Water vapor Analysis Difference at 700 mb (00UTC 25 August)



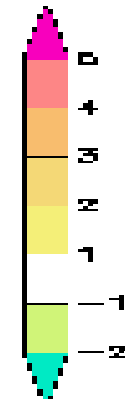
RO6km-CTRL



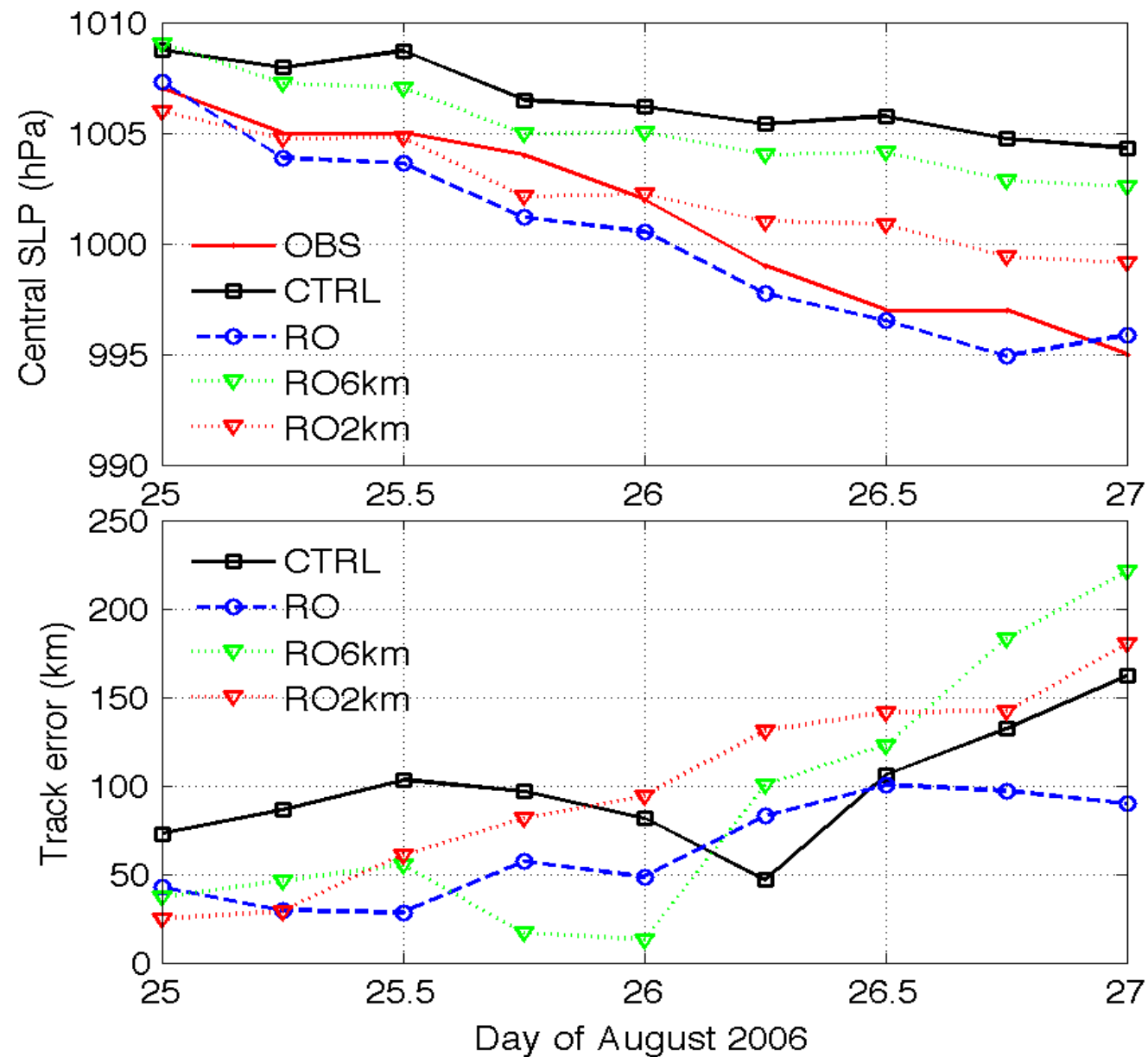
RO2km-
CTRL



RO-CTRL

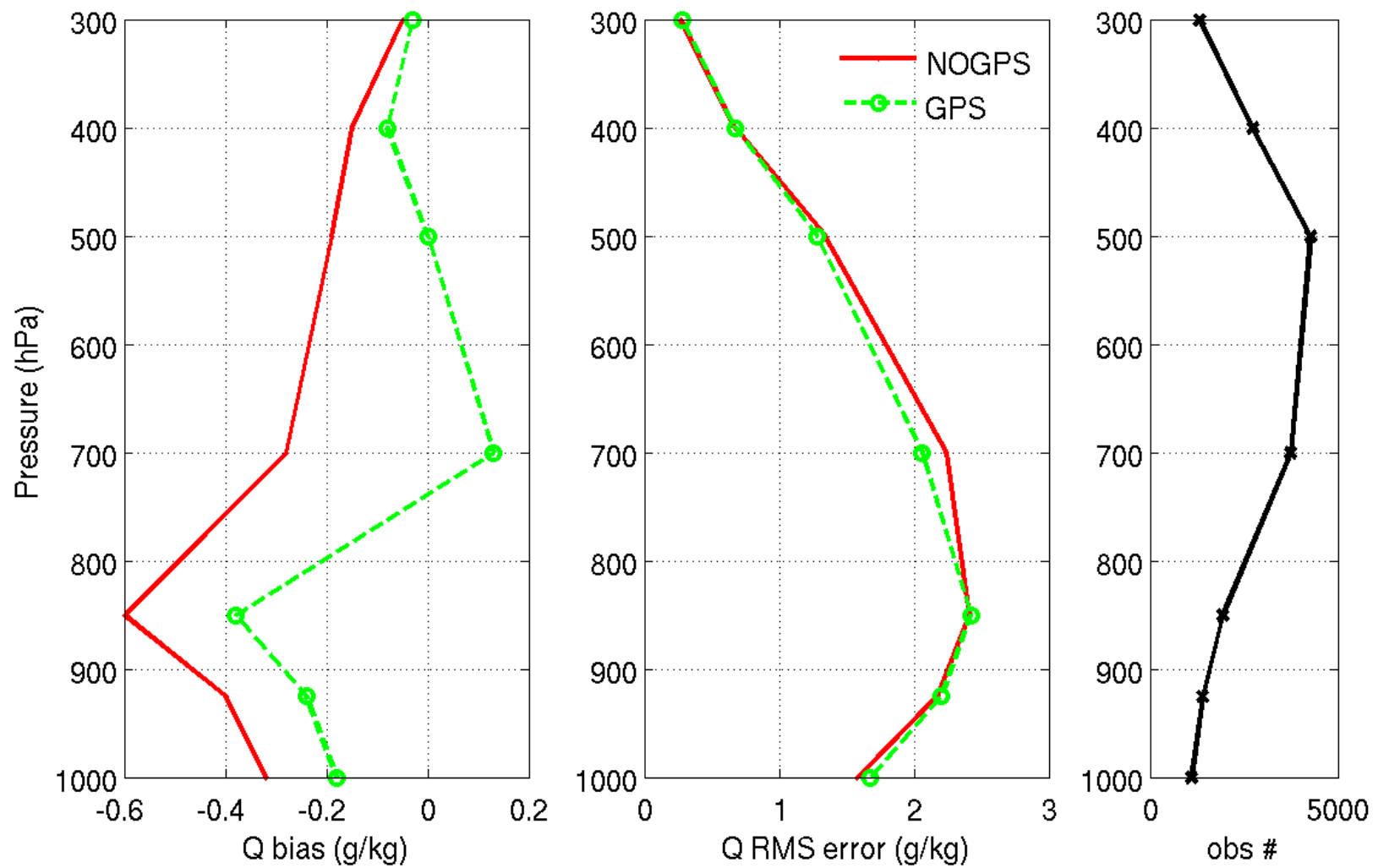


48h-forecast of Track errors and SLP Intensity (00UTC 25 August)



Summary of Ernesto Study

- Assimilation of GPS RO data adds moisture in the lower troposphere, and produces noticeable wind increments, consistent with the convective environment.
- GPS RO data in the lower troposphere is crucial for creating a favorable environment for hurricane genesis. If we miss the bottom 6km, we will fail to capture hurricane genesis. The bottom 2km is also important.
- Assimilation of GPS RO data produced improved analysis and subsequent forecasts both in terms of track and intensity.



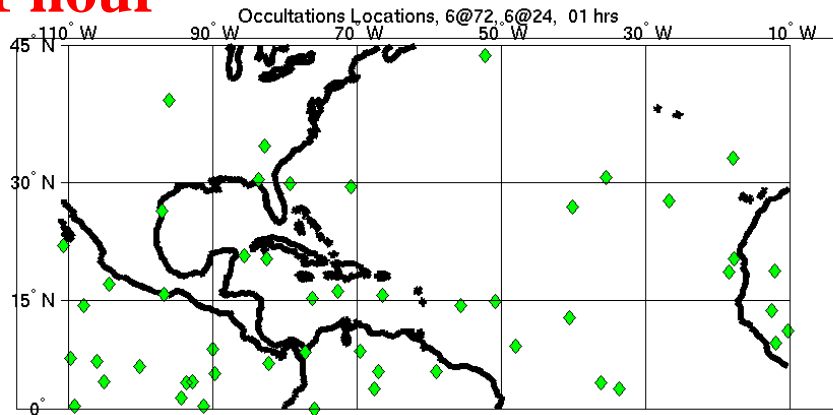
Verification of WRF/DART analysis by about 100 dropsondes during the Ernesto genesis stage.

FORMOSAT-7/COSMIC-2 Soundings

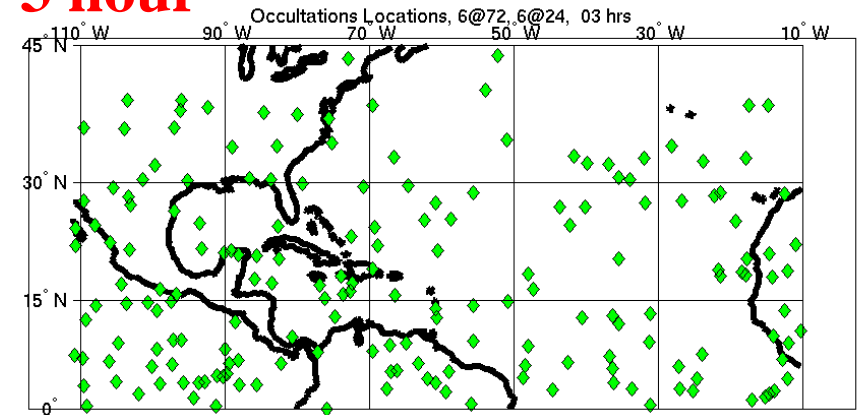
GPS and GLONASS

(6@72° , 6@24°)

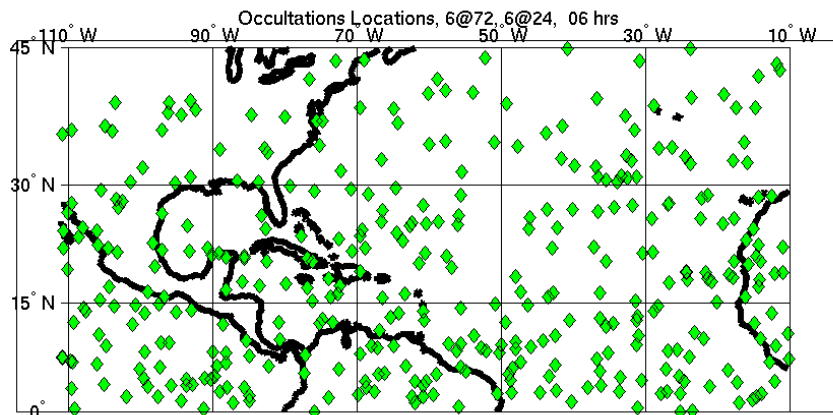
1 hour



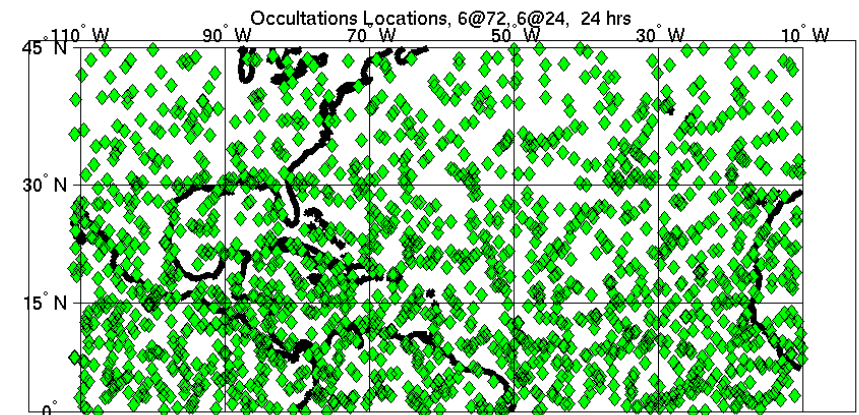
3 hour



6 hour



24 hour

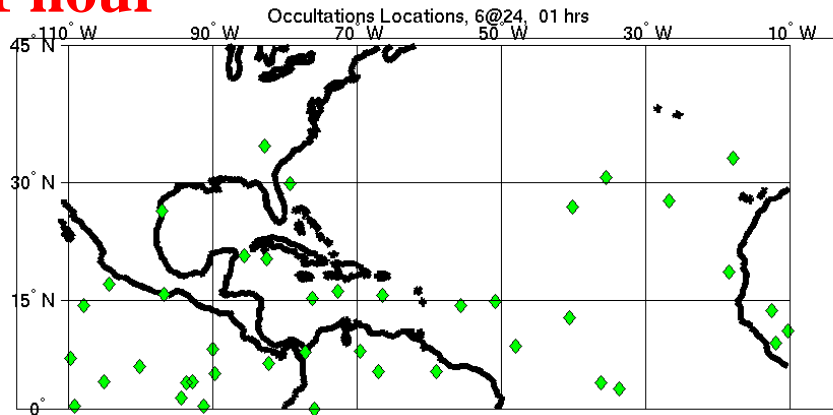


FORMOSAT-7/COSMIC-2 Soundings

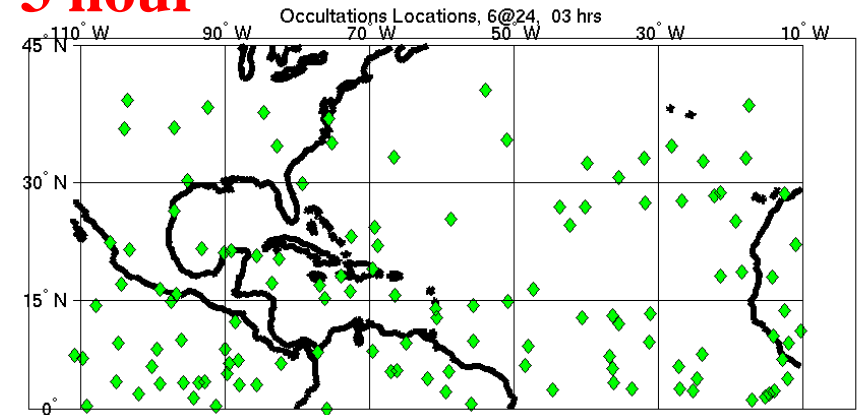
GPS and GLONASS

(6@24°)

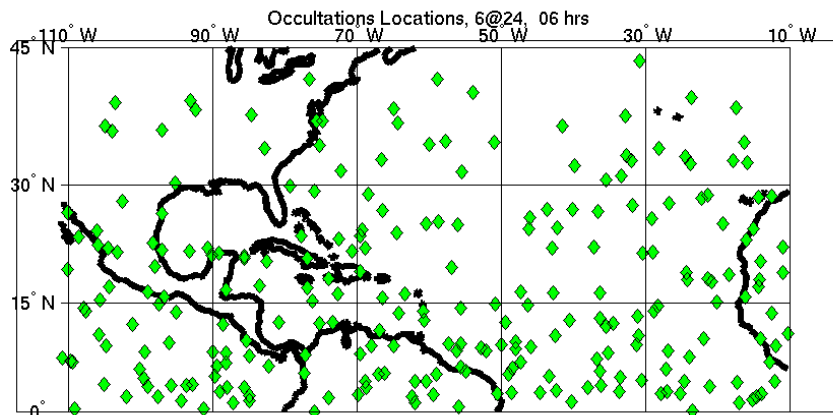
1 hour



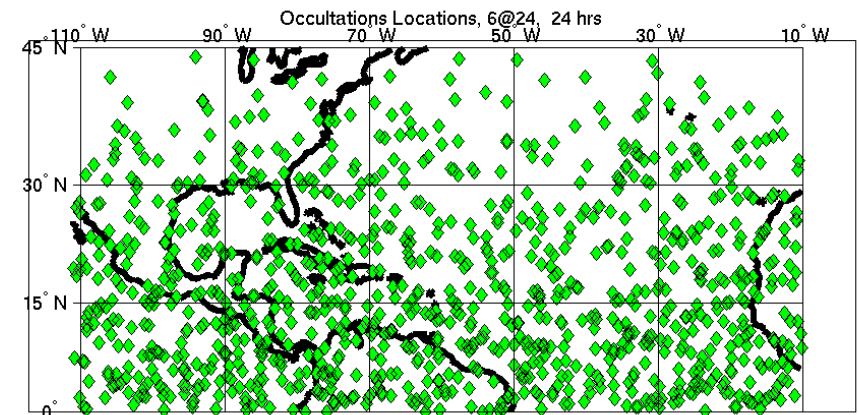
3 hour



6 hour



24 hour



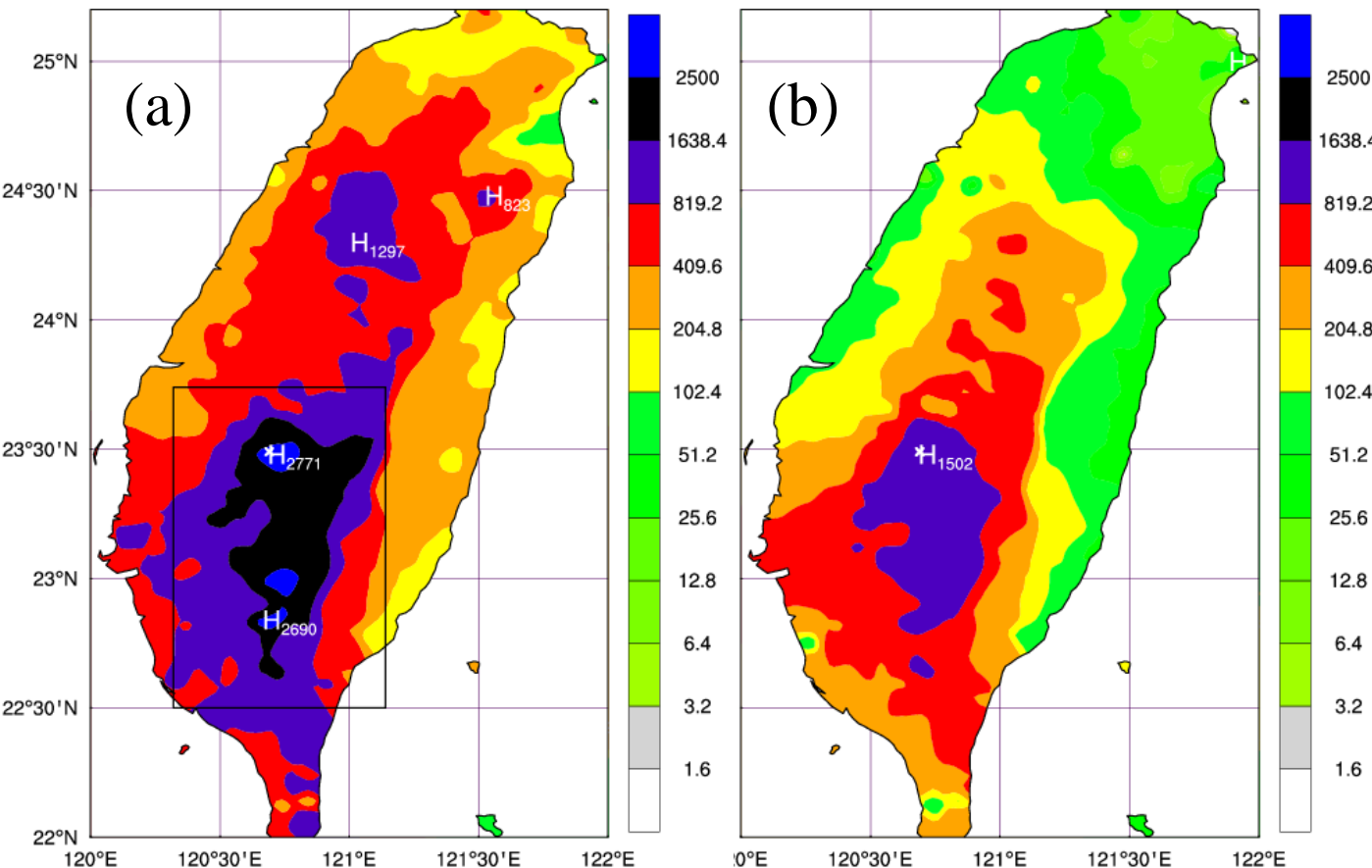
END

Impact of GPS RO data on Typhoon Morakot (2009)

Observed Rainfall of Typhoon Morakot (2009)

--- Objective analysis from ~450 automatic stations

- From August 6 to 10, 2009, Typhoon Morakot brought extraordinary rainfall over Taiwan, breaking 50 year's precipitation record, causing a loss of more than 700 people and estimated property damage exceeding US\$3.3 billion
- Maximum 24-h gauge value of **1700 mm (world record 1825 mm)**
- Maximum 96-h gauge value of **3739 mm** at Chiayi County



The spatial distribution of the objective analysis of the **observed rainfall** produced by Typhoon Morakot over Taiwan and surrounding islands (unit: mm): **(a) 96-h accumulated rainfall** on August 6-10; **(b) 24-h accumulated rainfall** on August 8-9. The white cross mark shows the maximum gauge value, 3739 mm in (a) and 1700 mm in (b). The box with black frame in (a) is defined as the verification target area, with latitudes from 22.50°N to 23.74°N, longitudes from 120.32°E to 121.14°E (about 130 × 90 square km).

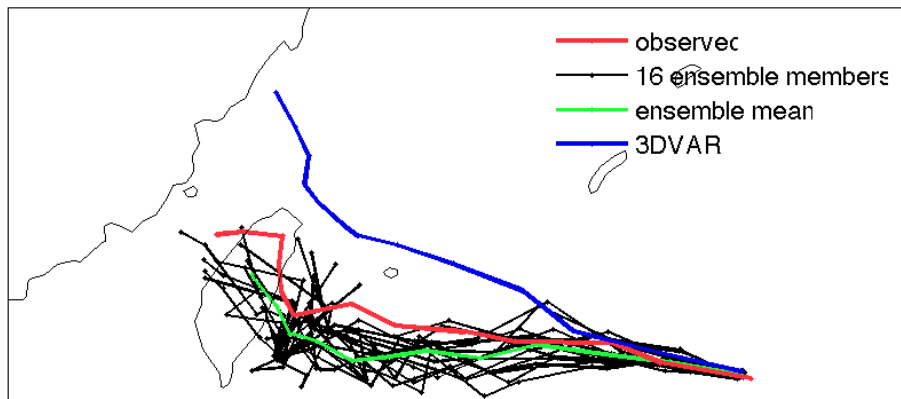
WRF/DART Analyses and Forecasts for Morakot (2009)

- Control (with GPS RO): CWB operational observations including TC BOGUS data, 6-hourly analysis cycle.
- NOGPS: remove the GPS RO data from the control run.
- Assimilations started 12UTC Aug. 3, 2009. 45km grid only for both assimilation and forecasts.
- CWB Typhoon WRF (TWRF) is also full cycled for the same period.
- Cost of the 16 ensemble forecasts is equivalent to one nested (45/15/3km) deterministic forecast.

Forecast initialized at 12 UTC 5 August

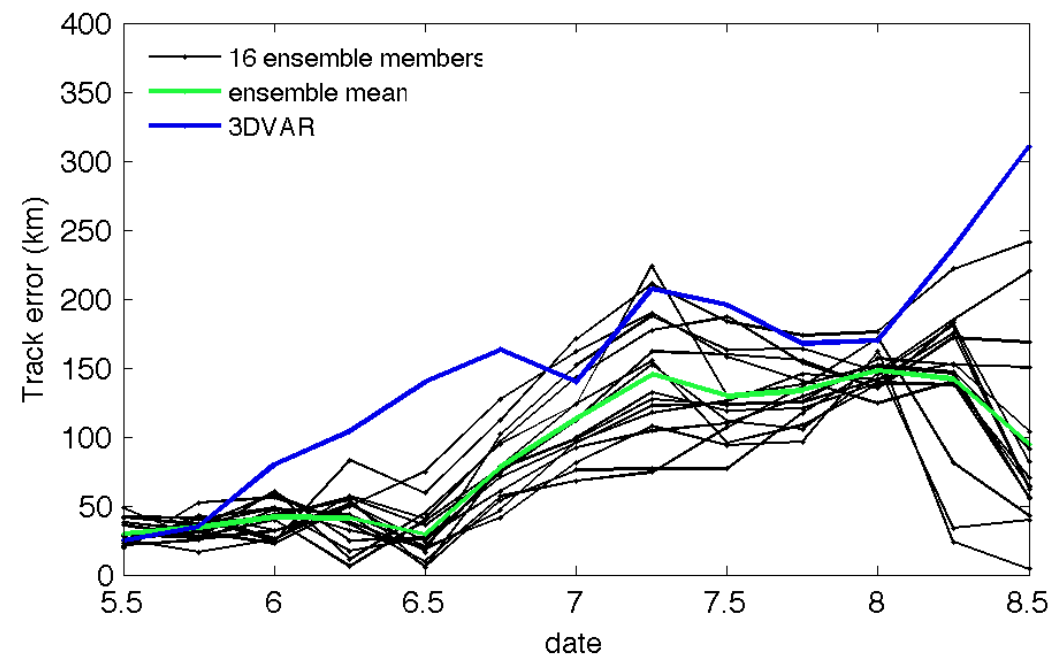
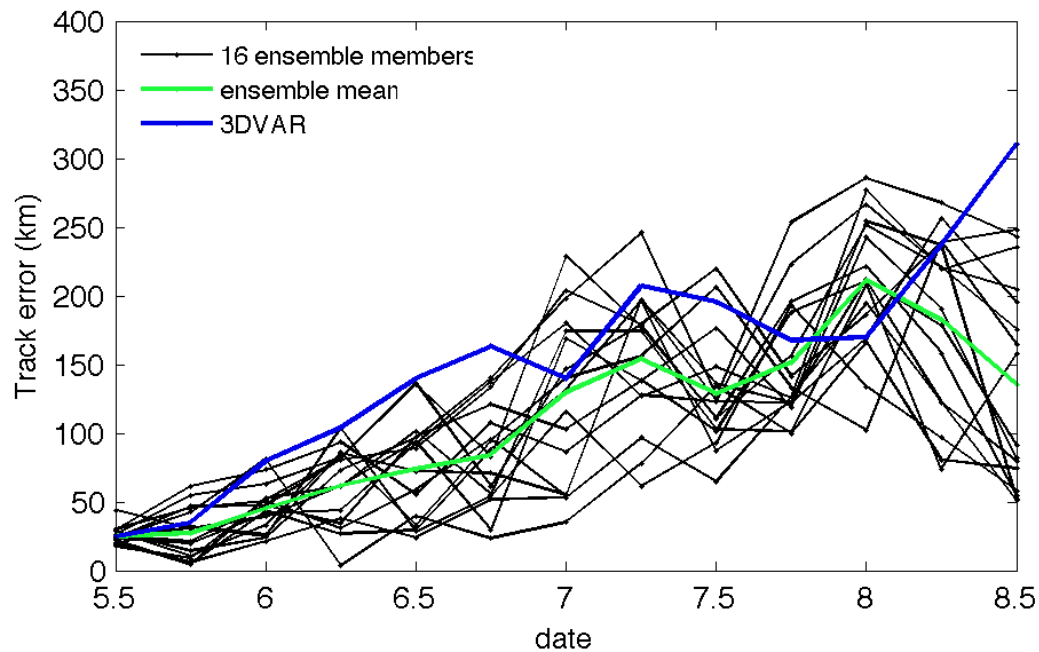
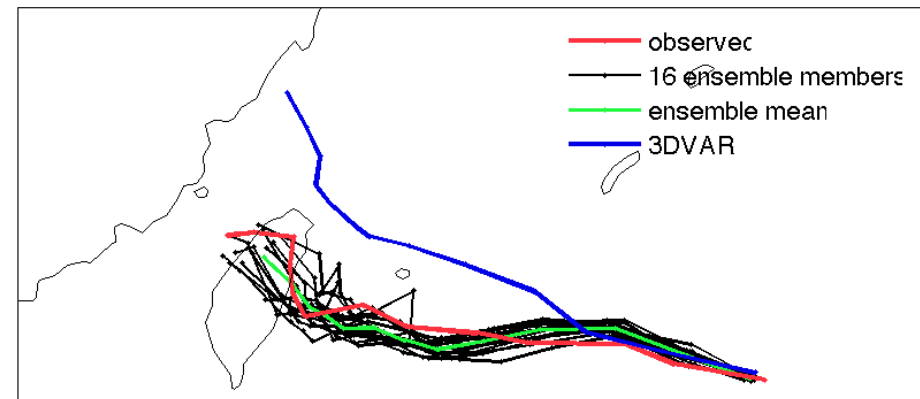
No GPS

72h ensemble forecasts from 12Z 5 August 2009 TC Morakot



With GPS

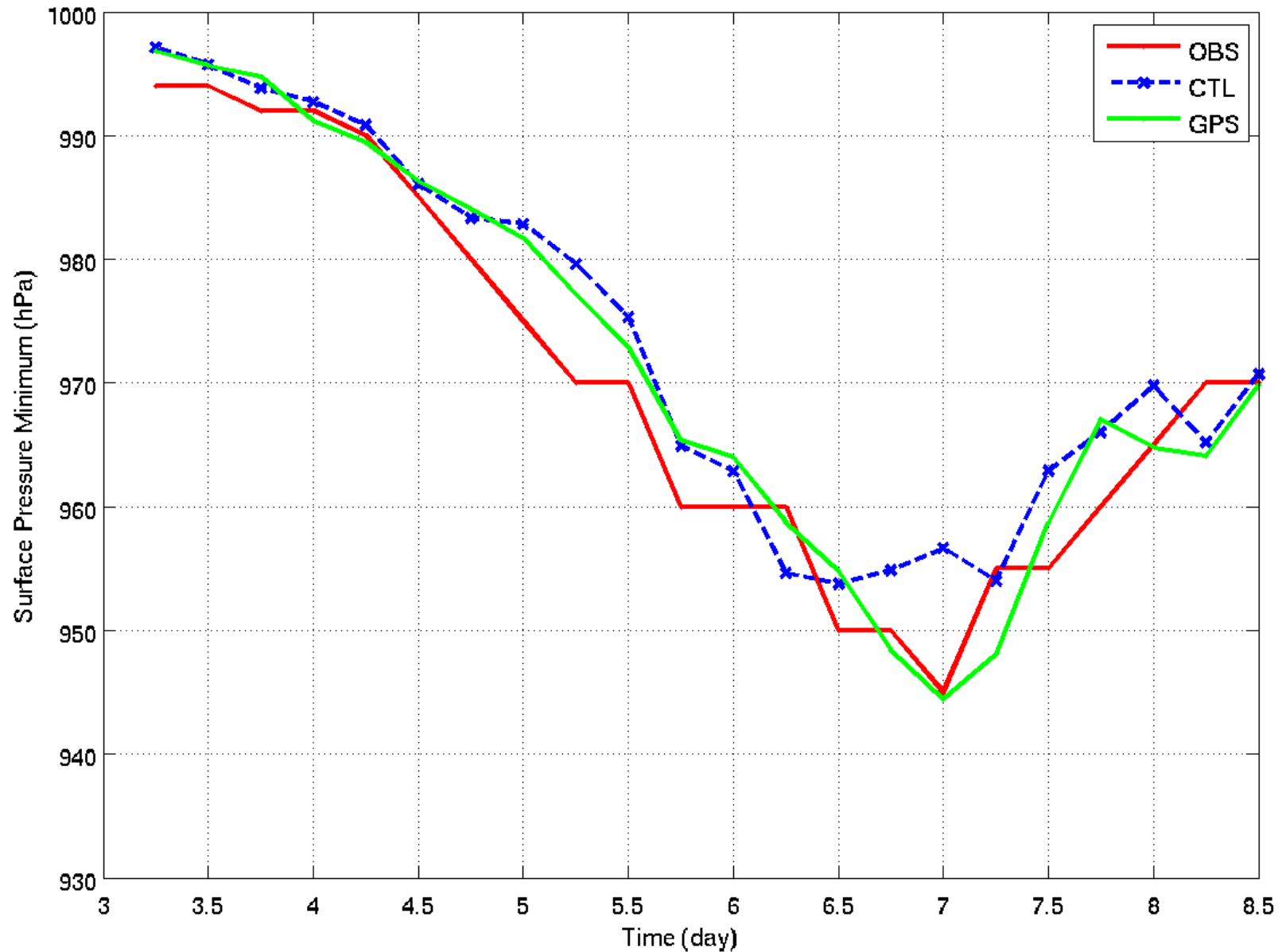
72h ensemble forecasts from 12Z 5 August 2009 TC Morakot



Assimilation experiments for Morakot

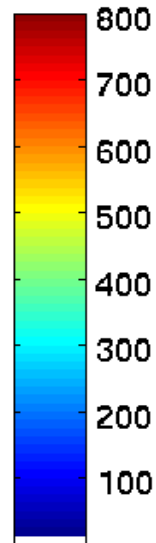
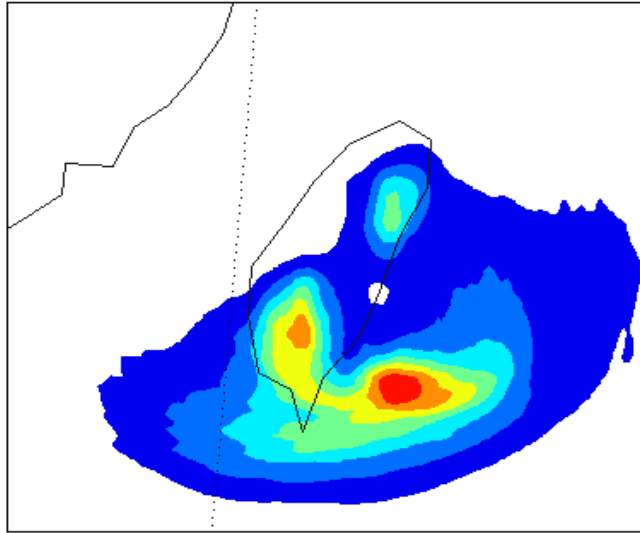
- Assimilation from 00Z August 3 to 18Z August 8, 2009 with 2-hourly cycling.
- 36km analysis grid with 35 levels
- 48h Forecast with nest grids 36km/12km/4km starting at August 7 00Z.
- CWB observations are used
- CTL run: Assimilate CWB conventional observations
- GPS run: CTL run + COSMIC data.

SLP intensity analyses (August 3 06Z - 8 18Z)

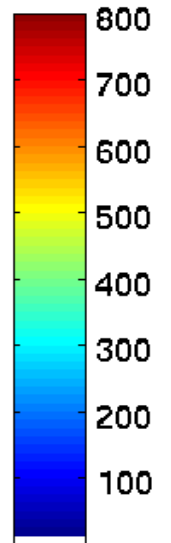
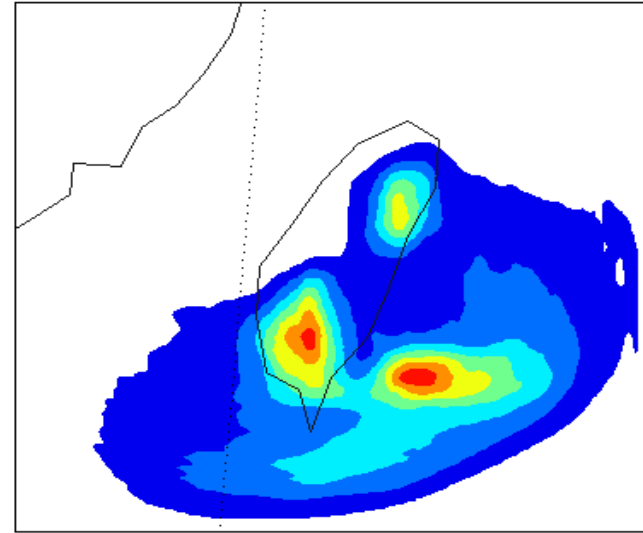


24h Rain forecast (August 7 - 8 00Z)

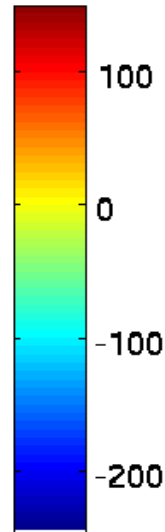
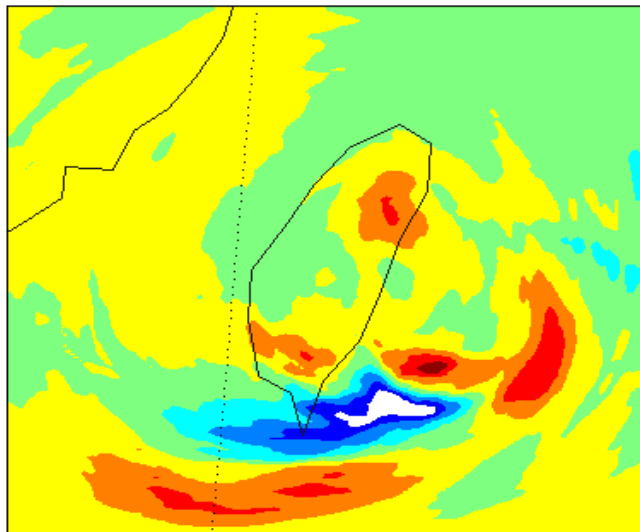
24h Prep forecast, ctl, Aug 7-8



24h Prep forecast, gps, Aug 7-8

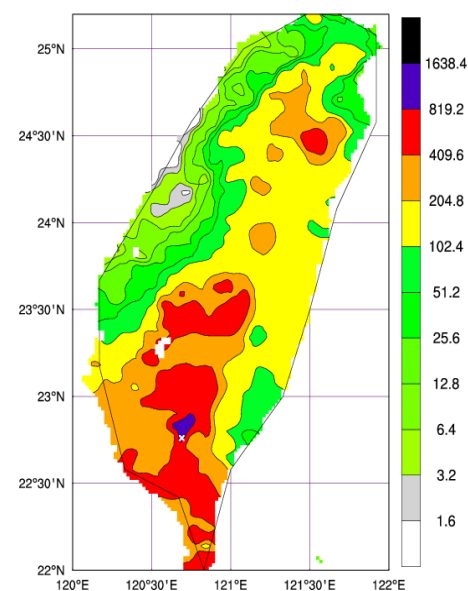


24h Prep forecast, gps - ctl, Aug 7-8



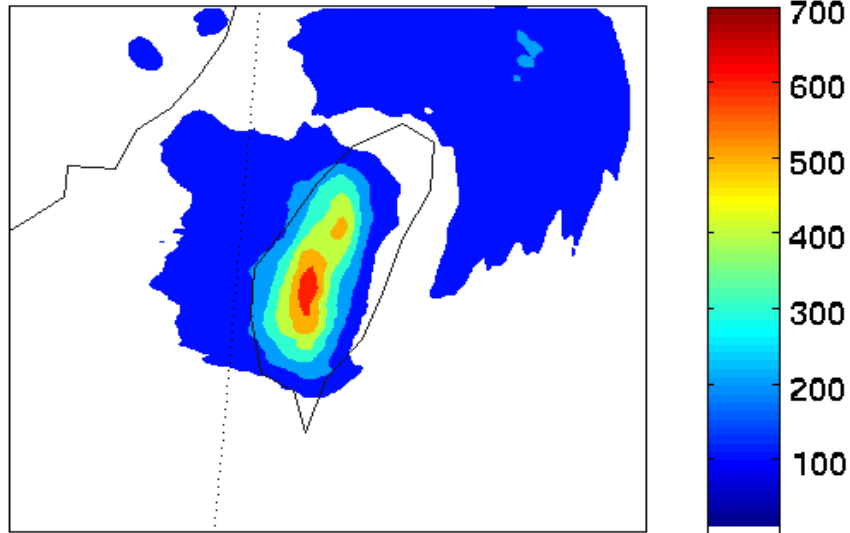
Obs pre on obs grid

Obs pre from 0700UTC to 0800UTC max1364 mm

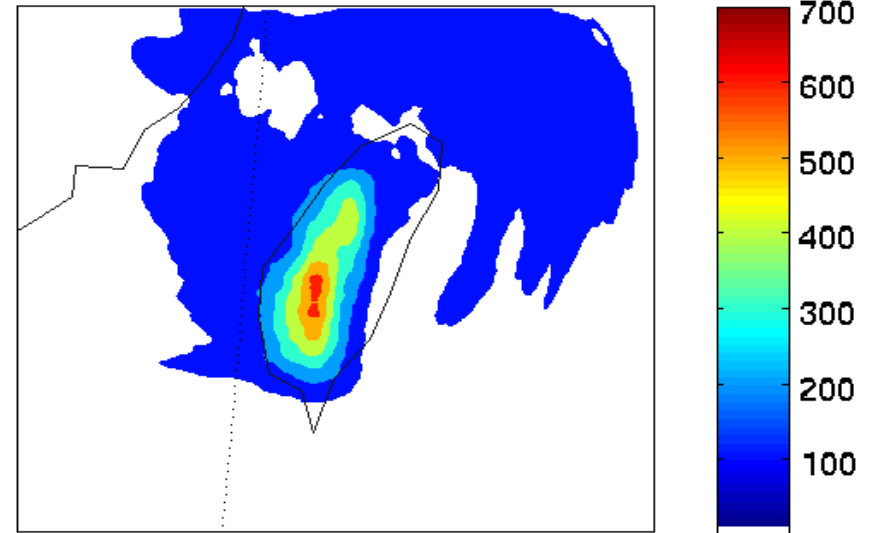


48h Rain forecast (August 8 - 9 00Z)

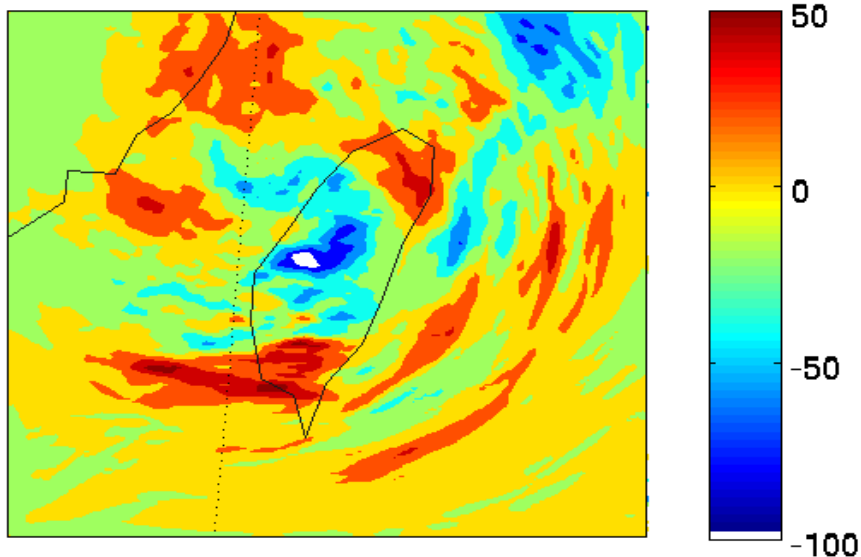
48h Prep forecast, ctl, Aug 8-9



48h Prep forecast, gps, Aug 8-9

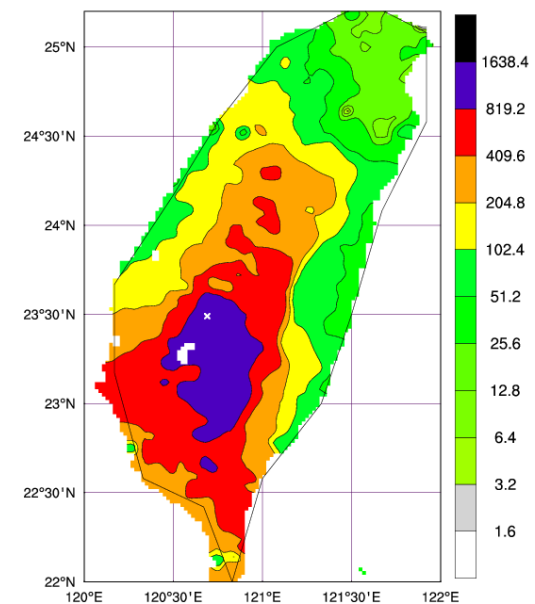


48h Prep forecast, gps - ctl, Aug 8-9



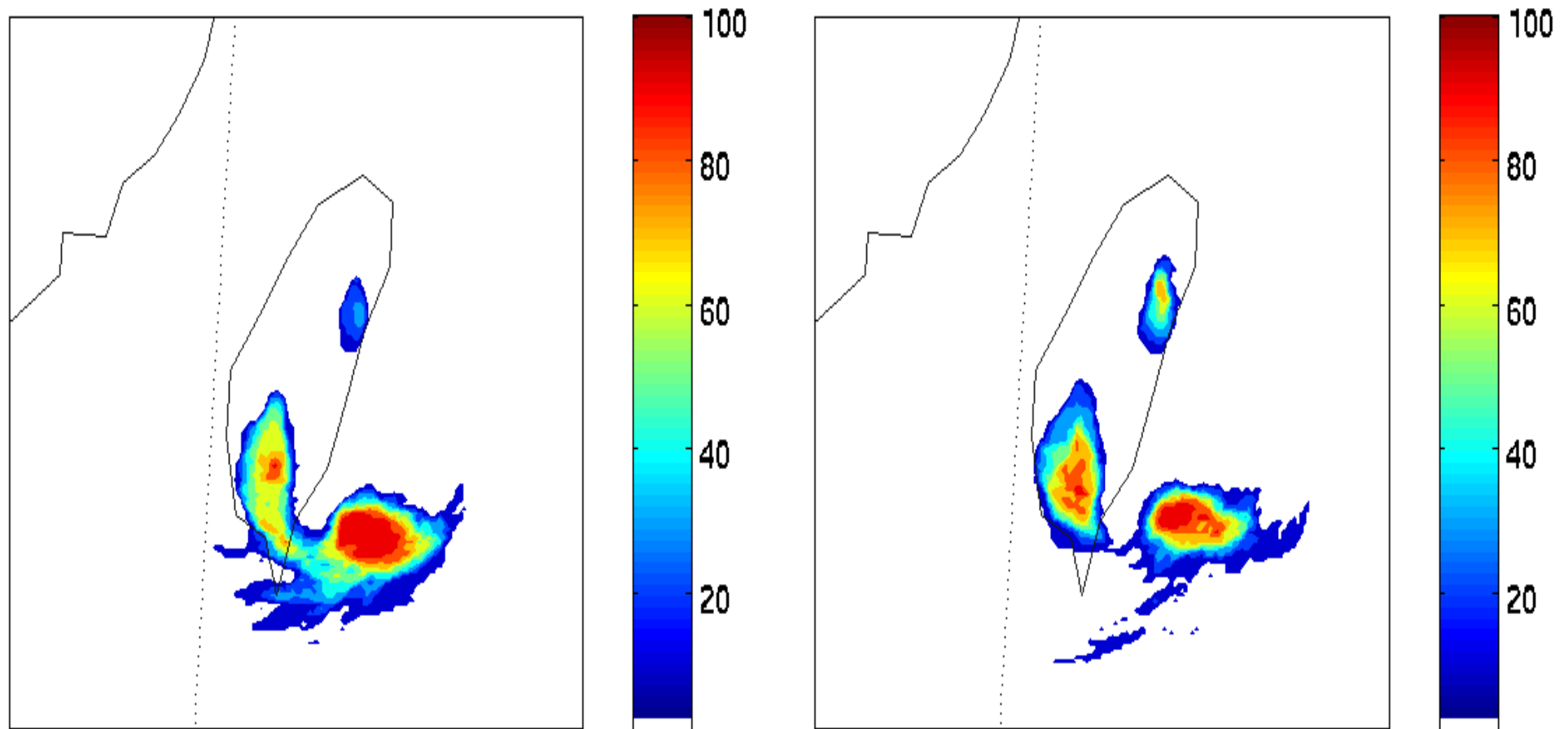
Obs pre on obs grid

Obs pre from 0800UTC to 0900UTC max1700 mm



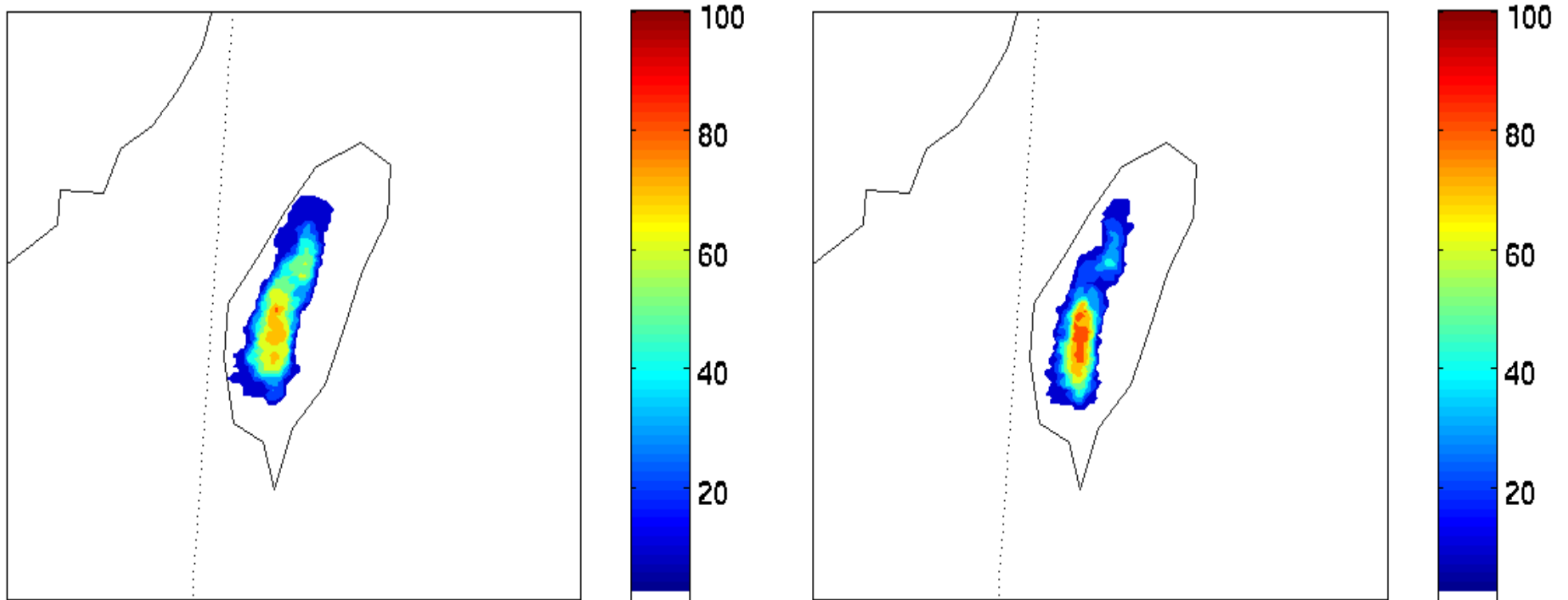
Rain Probability Forecast (August 7-8 00Z)

Probability forecast (% , >500mm, Aug 7-8 00Z), CTL Probability forecast (% , >500mm, Aug 7-8 00Z), GPS

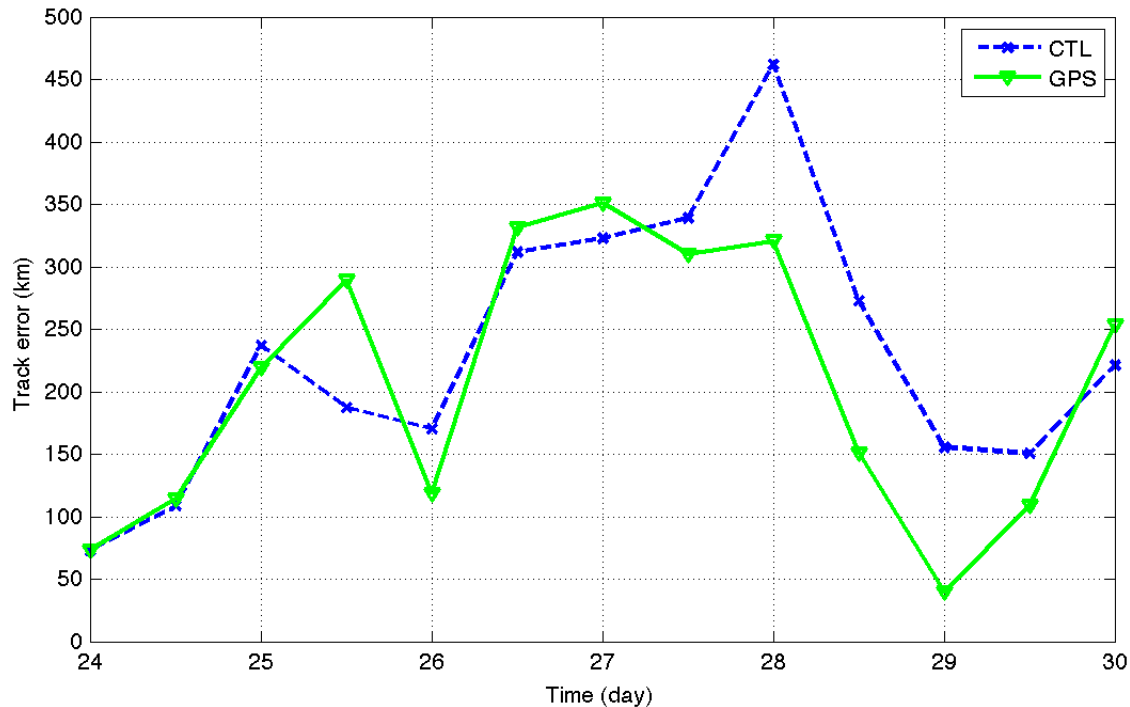


Rain Probability Forecast (August 8 - 9 00Z)

Probability forecast (% , >500mm, Aug 8-9 00Z), CTL Probability forecast (% , >500mm, Aug 8-9 00Z), GPS



Typhoon Prediction During T-PARC



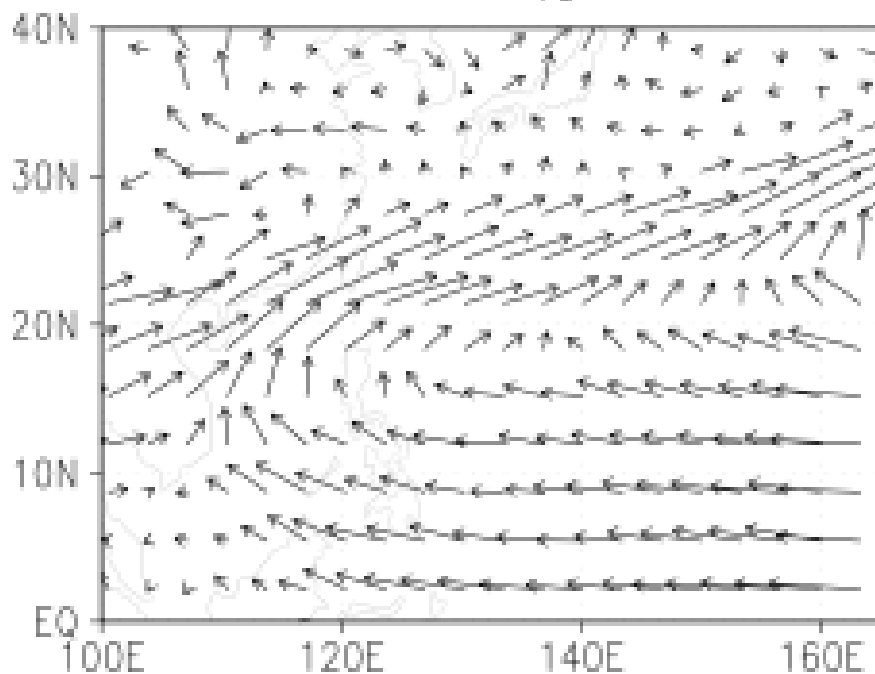
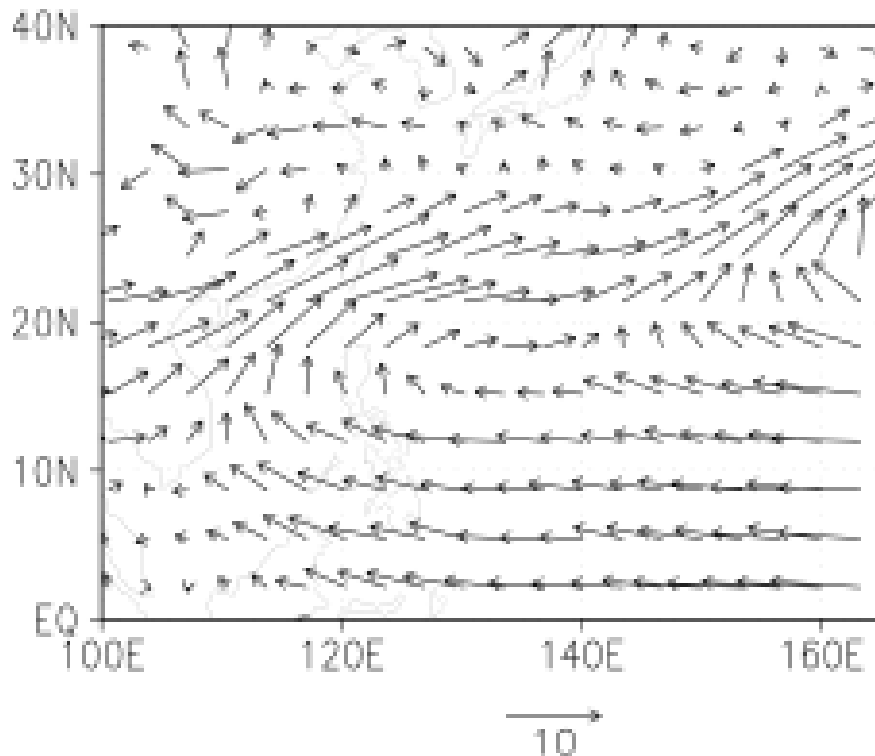
Assimilation of GPSRO data from COSMIC improved the quality of regional analysis and typhoon track errors. For four storms in T-PARC 2008, the average improvement is 13%.

48-h of track forecast errors for Typhoon Jangmi (2008) with and without COSMIC.

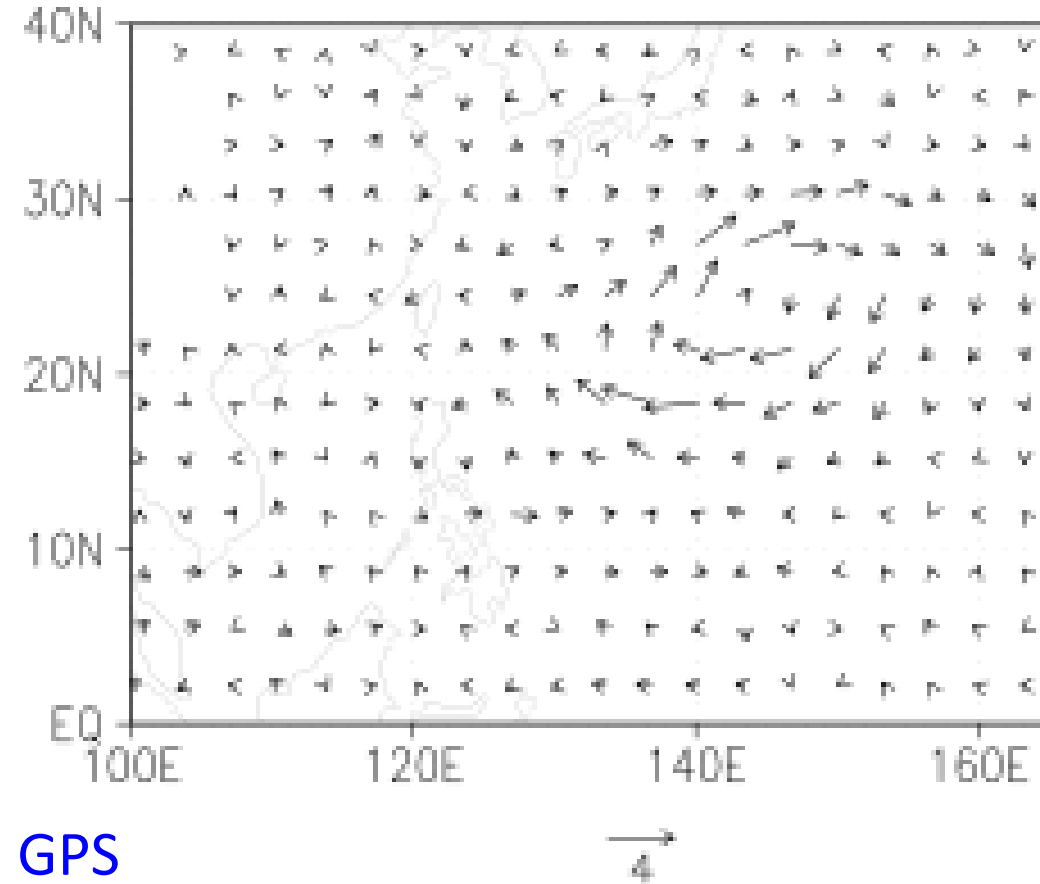
Table 2: 48-hour forecasts track RMS errors (km).

Typhoon Name	Control forecasts	COSMIC forecasts
Sinlaku	366 km	339 km
Hagupit	323 km	289 km
Nuri	300 km	249 km
Jangmi	254 km	231 km
Mean	311 km	277 km

From H. Liu and Jeff Anderson



Difference



Two week EnKF assimilation, 1-14 June 2007, 850 mb wind field.

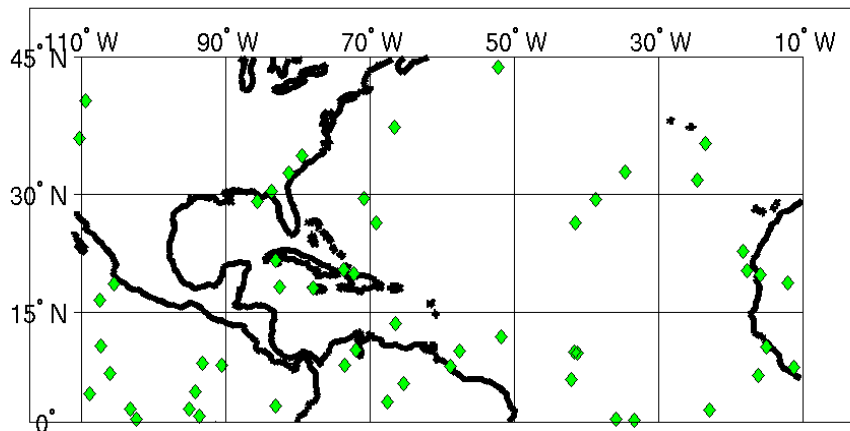
COSMIC-II Soundings

Geographic Coverage

(6@72° , 6@24°)

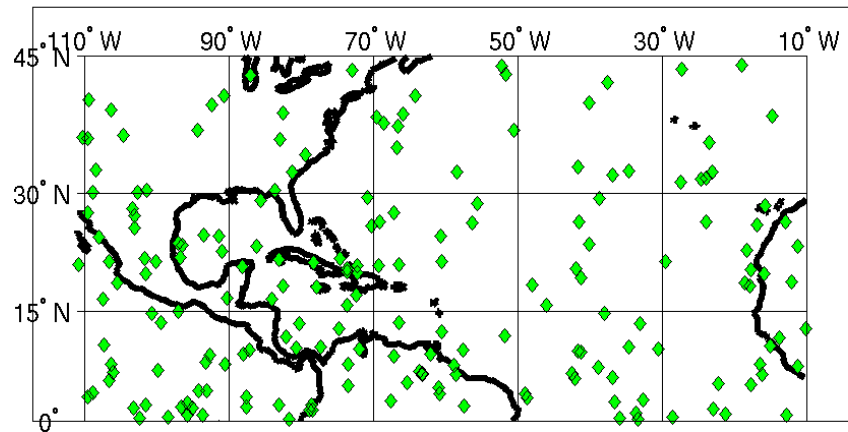
1 hour

Occultations Locations, 6@72, 6@24, 01 hrs



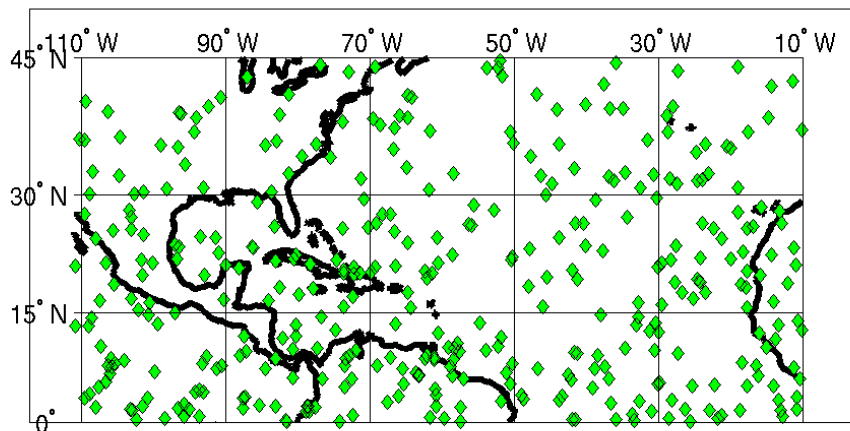
3 hour

Occultations Locations, 6@72, 6@24, 03 hrs



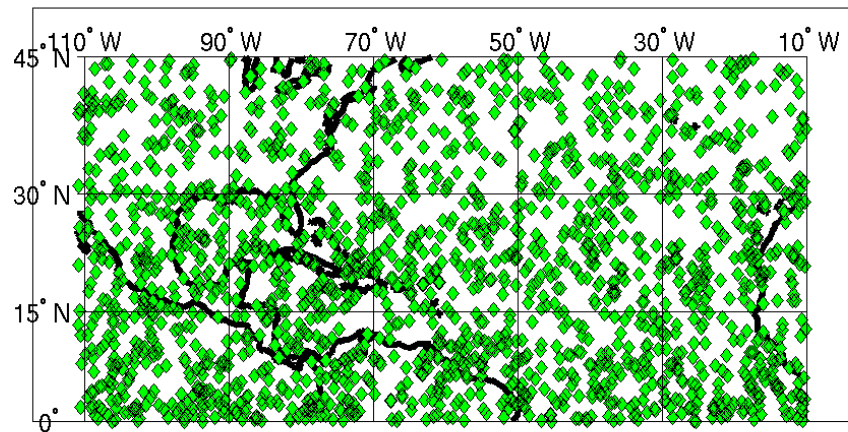
6 hour

Occultations Locations, 6@72, 6@24, 06 hrs



24 hour

Occultations Locations, 6@72, 6@24, 24 hrs



Summary

- GPSRO observations are not affected by clouds and precipitation
- GPSRO observations provide three-dimensional water vapor information over the tropics, which are crucial for:
 - Tropical cyclone genesis
 - Tropical cyclone intensity forecast
 - Tropical cyclone track forecast
- Current FORMOSAT-3/COSMIC sounding distribution is NOT optimal for tropical prediction. The data density is the lowest over the tropics (0.4 sounding over 500 km x 500 km in one day).
- FORMOSAT-7/COSMIC-2, with 10 times more soundings will significantly improve the skills of tropical cyclone prediction:
 - Improve track, intensity and rainfall forecast for typhoons
 - Directly contribute to all the goals of NOAA's Hurricane Forecast Improvement Project (HFIP)

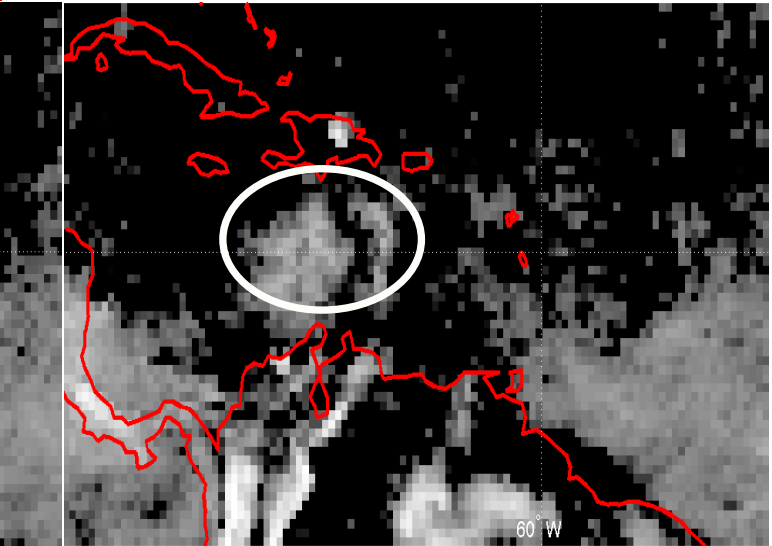
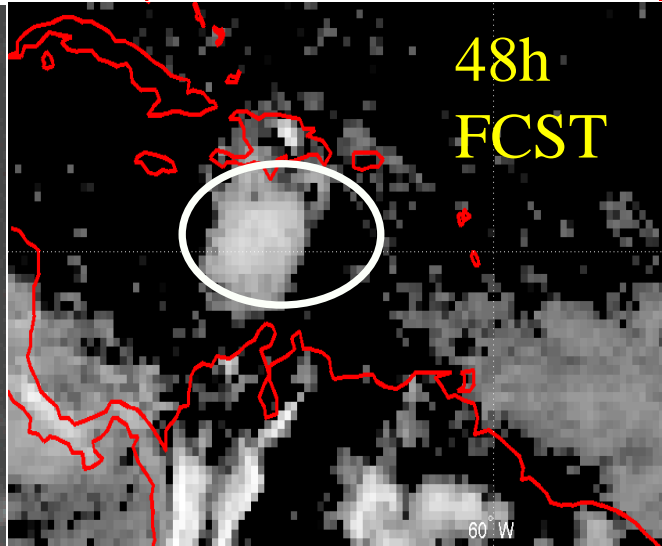
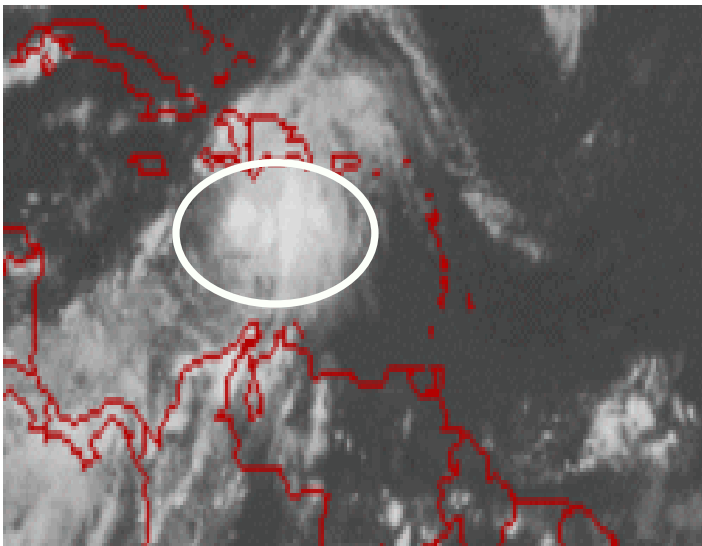
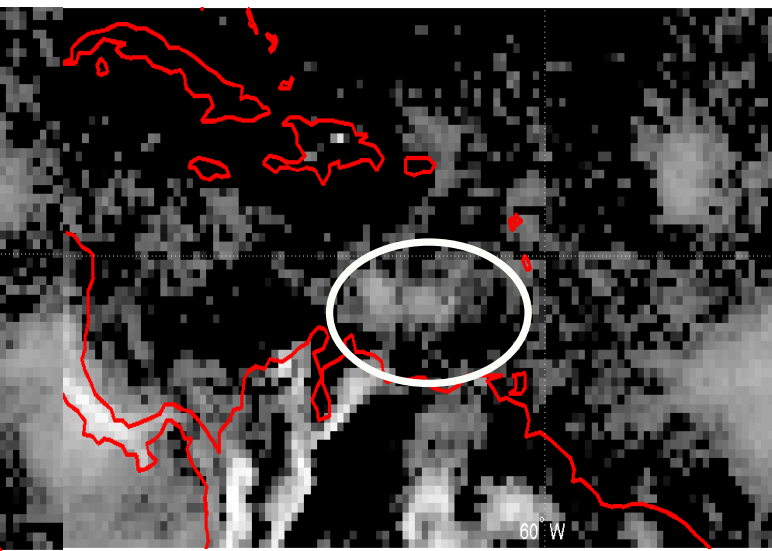
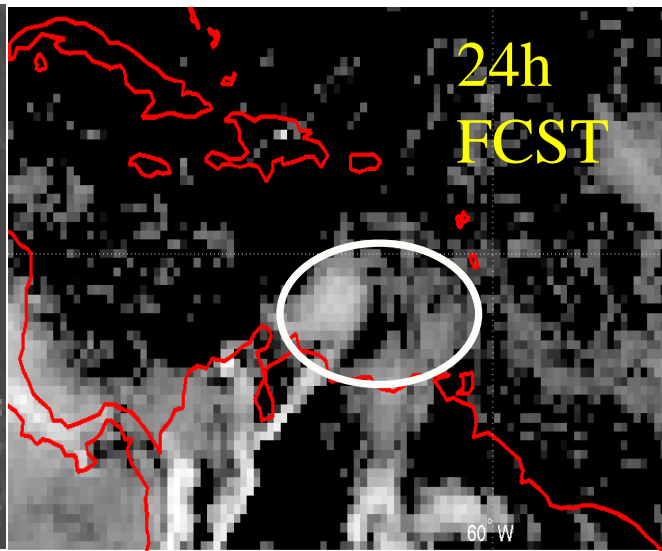
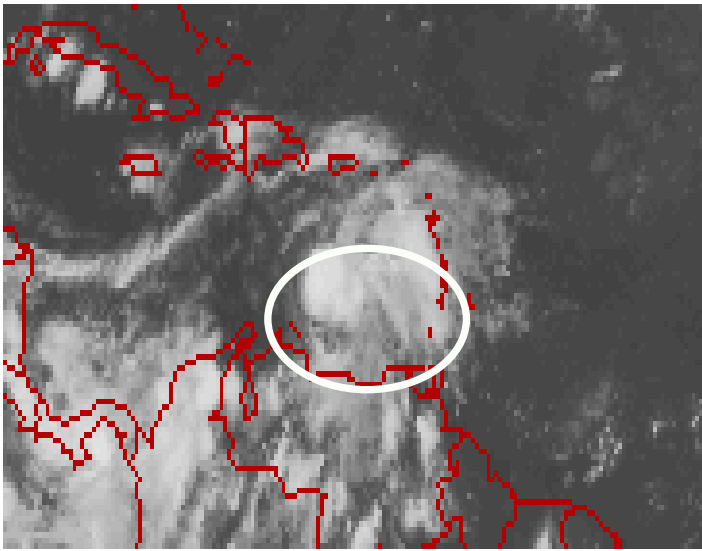
Back-up Slides

Total Integrated Water Vapor of 48-hour Forecasts (00UTC 25 August)

IR image

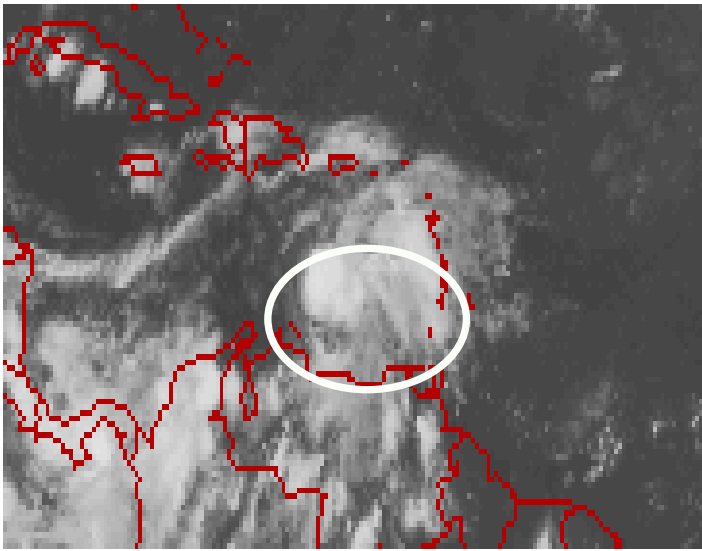
RO

CTRL

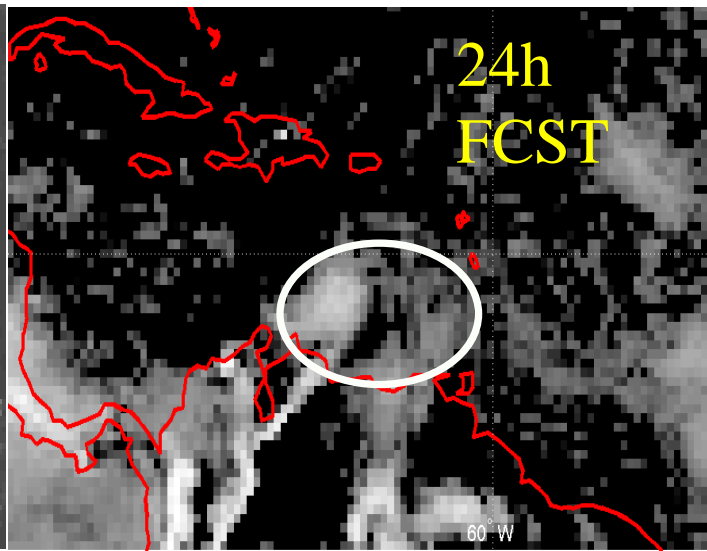


48-hour Forecasts of Ernesto (2006) with Assimilation of GPS and Conventional Observations

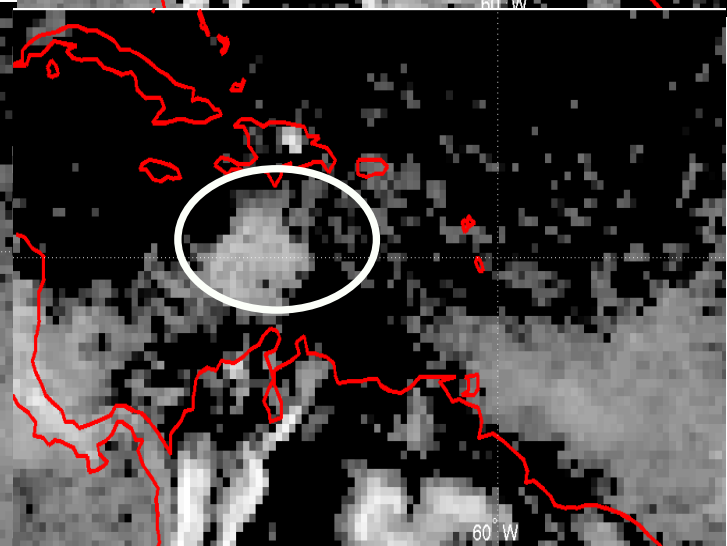
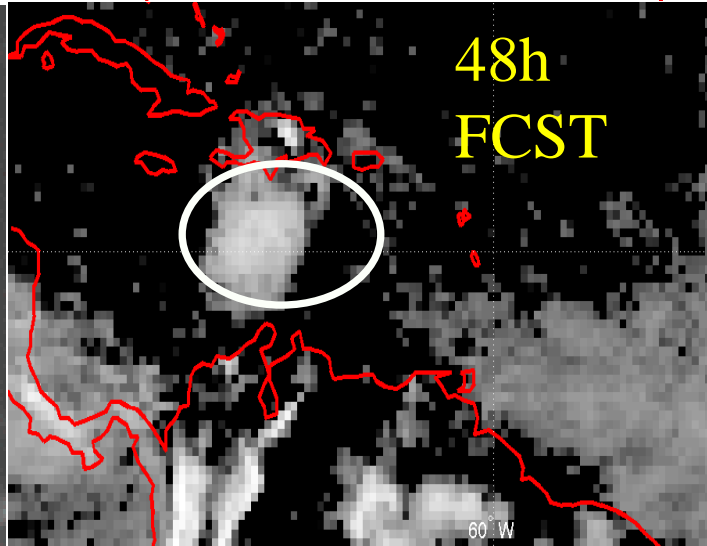
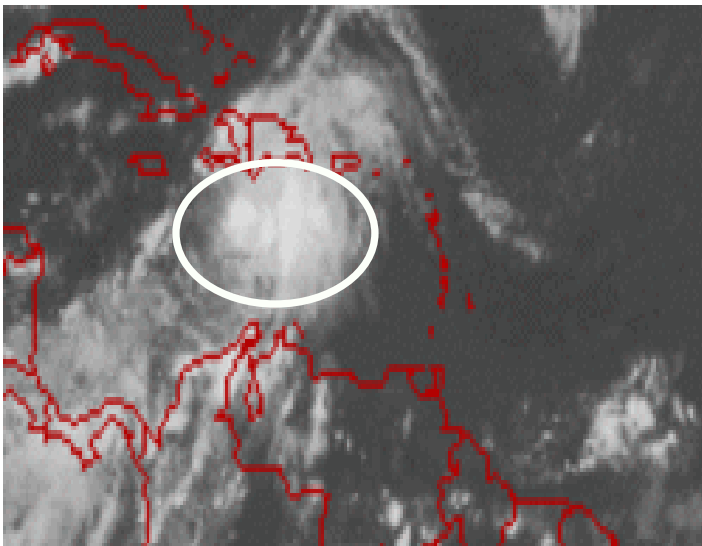
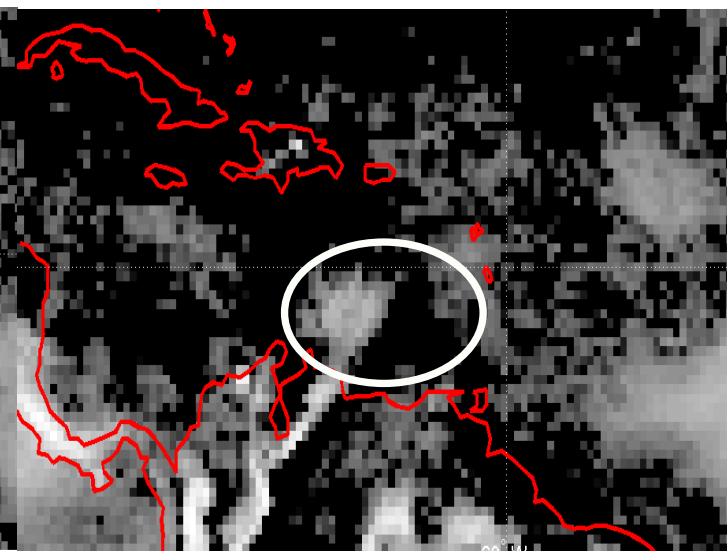
IR Image



RO



RO6km



Assimilation of GPS > 6km shows less positive impact

Summary of Morakot Study

- Assimilation of the GPS data:
 - Improve analysis and prediction of typhoon track
 - Improve rainfall prediction
- Performance of ensemble-based EnKF (WRF/DART) is superior to WRF-3DVAR system
- Positive impact of GPSRO is also seen in WRF-3DVAR system