A Study on Airborne GPS Radio Occultations (ROs) and their Impact on Hurricane Karl (2010) Forecast

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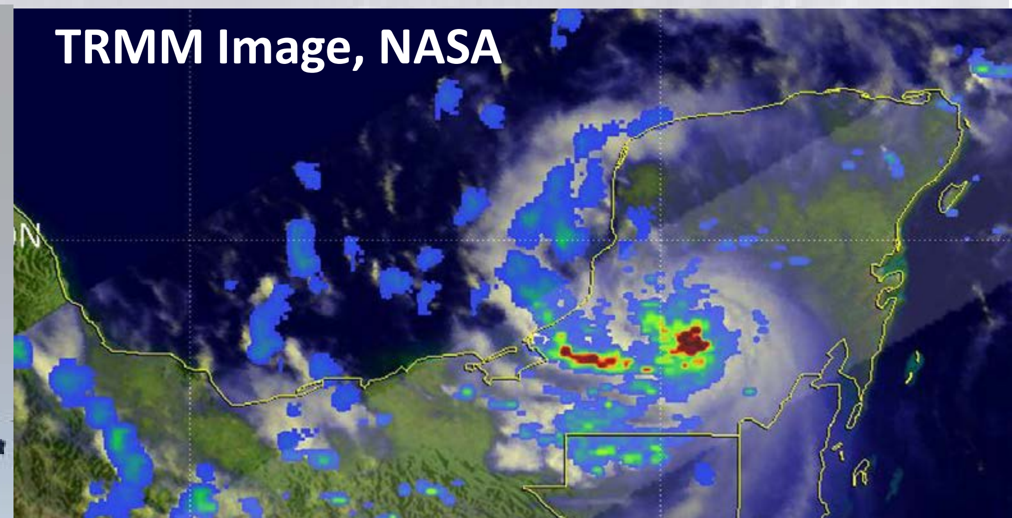
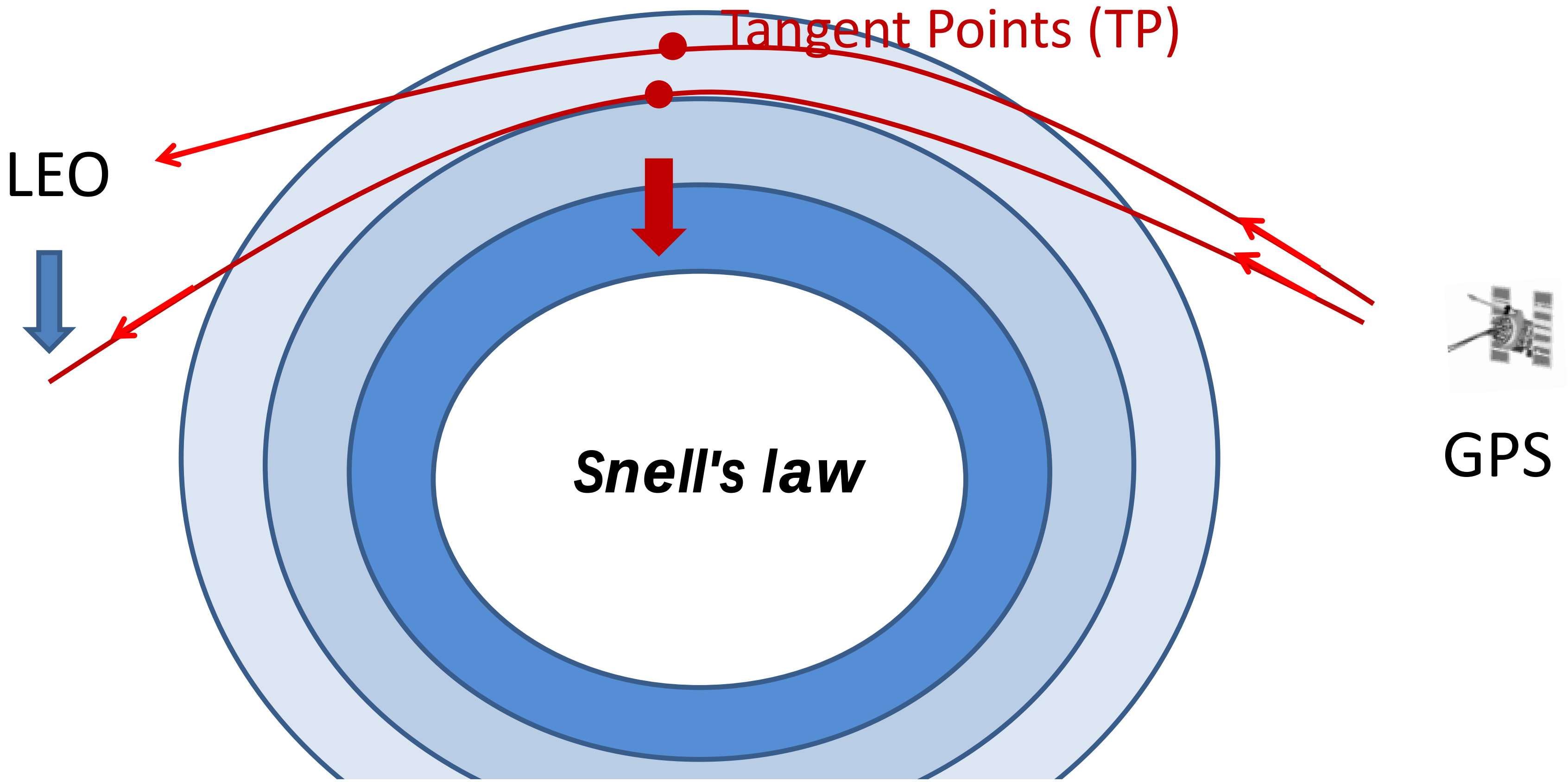
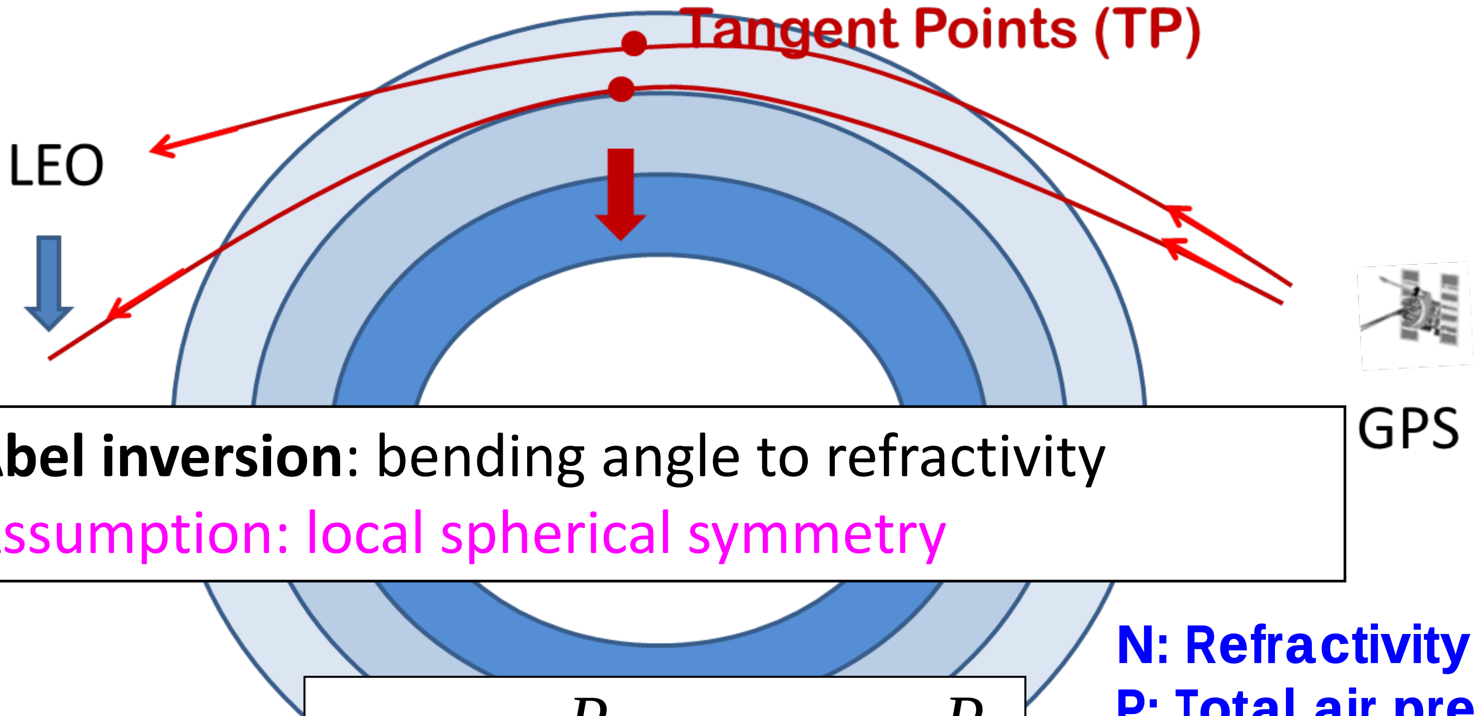


Spaceborne GPS Radio Occultation (RO)



- **GPS RO measurements are nearly weather free !**
- **Have a great vertical resolution !**

Refractivity



Abel inversion: bending angle to refractivity

Assumption: local spherical symmetry

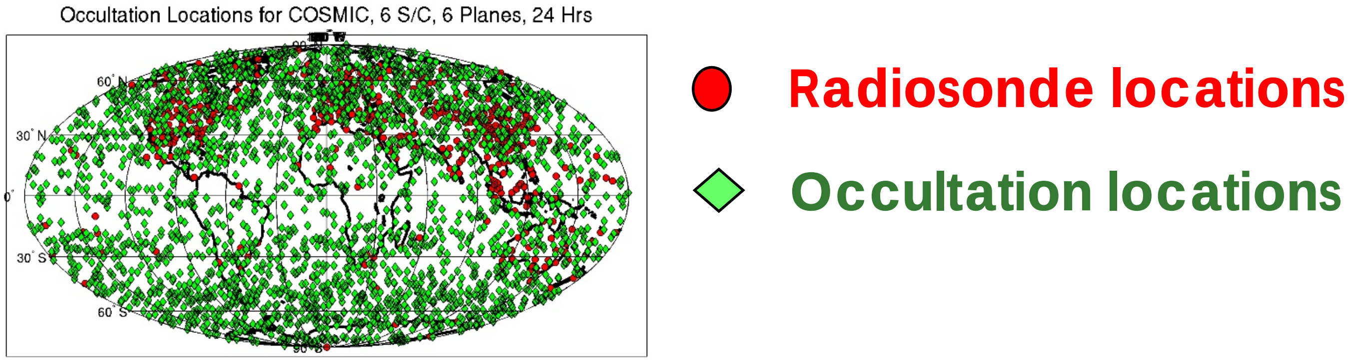
$$N \approx 77.6\frac{P}{T} + 3.73\times10^{5}\frac{P_w}{T^2}$$

N: Refractivity
P: Total air pressure
T: Air temperature
Pw: Water vapor pressure

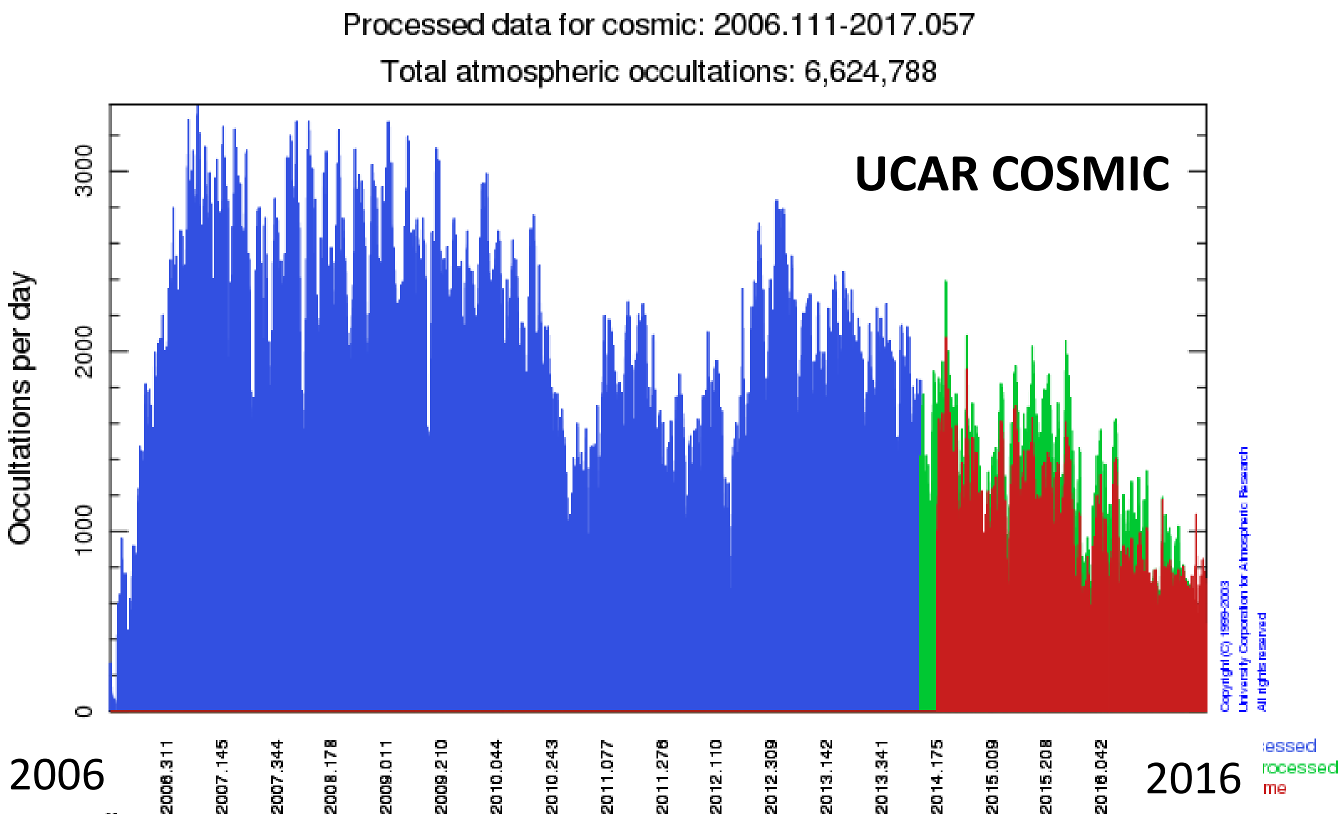
Observable = phase data ➡ Doppler shift ➡ bending angle ➡ refractivity

The RO data provide <u>temperature, moisture, and pressure</u> information.

COSMIC 2006



Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs
60° N
30° N
0°
30° S
60° S
Radiosonde locations
Occultation locations



Processed data for cosmic: 2006.111-2017.057
Total atmospheric occultations: 6,624,788
UCAR COSMIC
Occultations per day
0
1000
2000
3000
2006
2008.311
2007.145
2007.344
2008.178
2009.011
2009.210
2010.044
2010.243
2011.077
2011.276
2012.110
2012.309
2013.142
2013.341
2014.175
2015.009
2015.208
2016.042
2016
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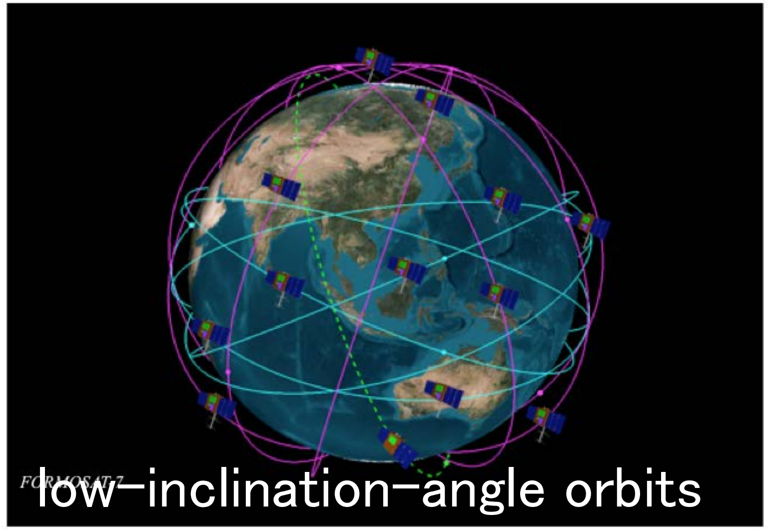
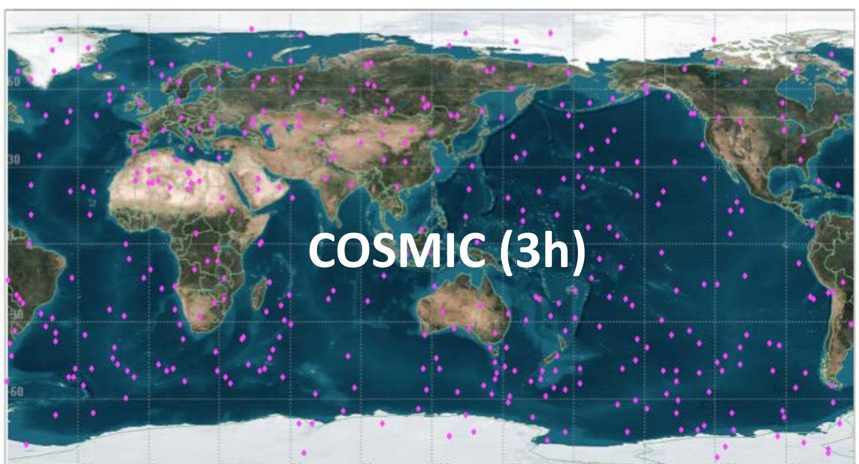
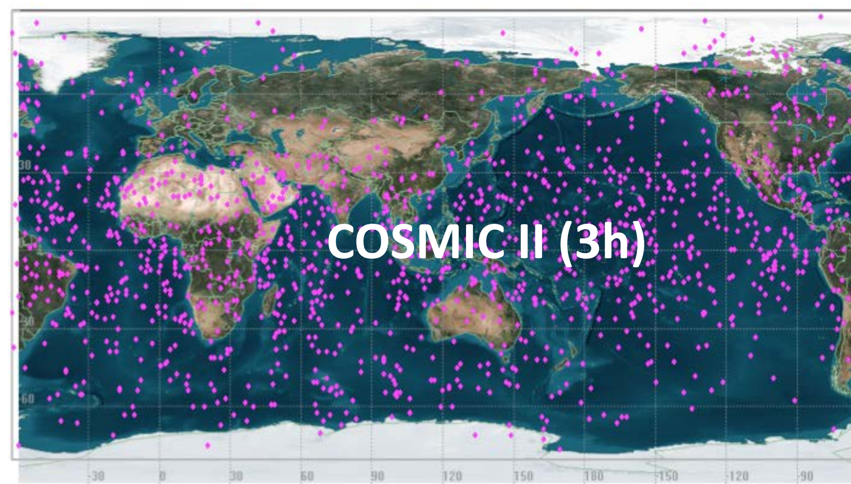
All rights reserved

COSMIC-II 2017



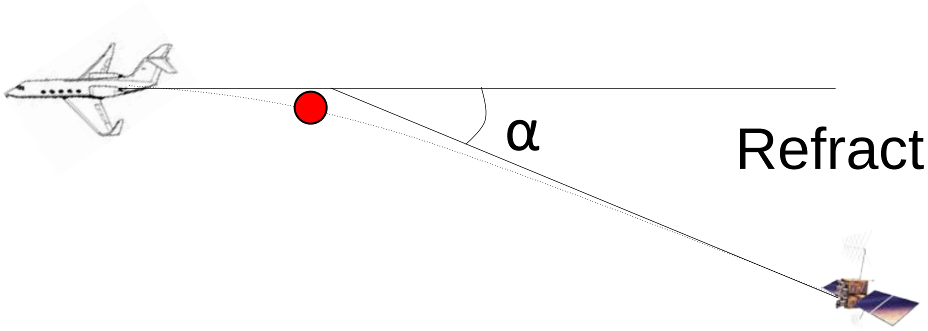
UCAR COSMIC

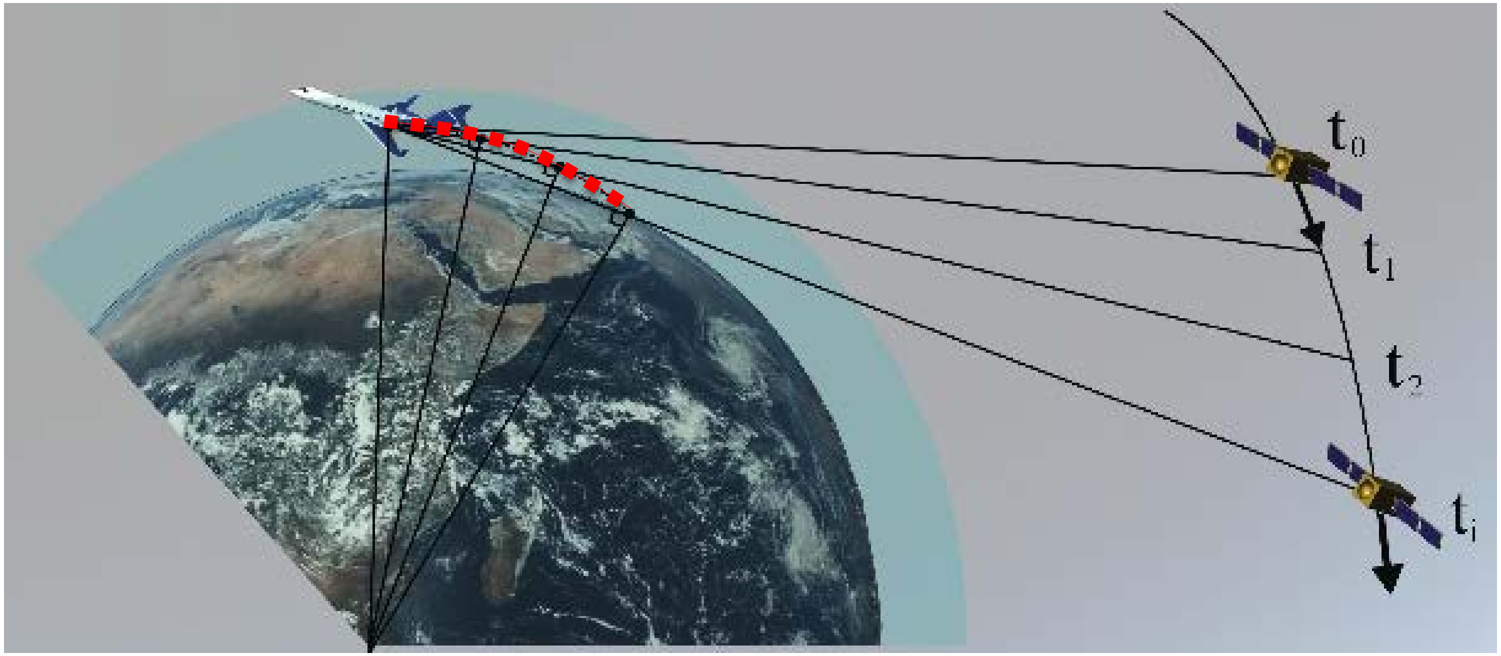




Air-borne GPS RO

Side-looking GPS receiver tracks setting and rising satellites





Motivation

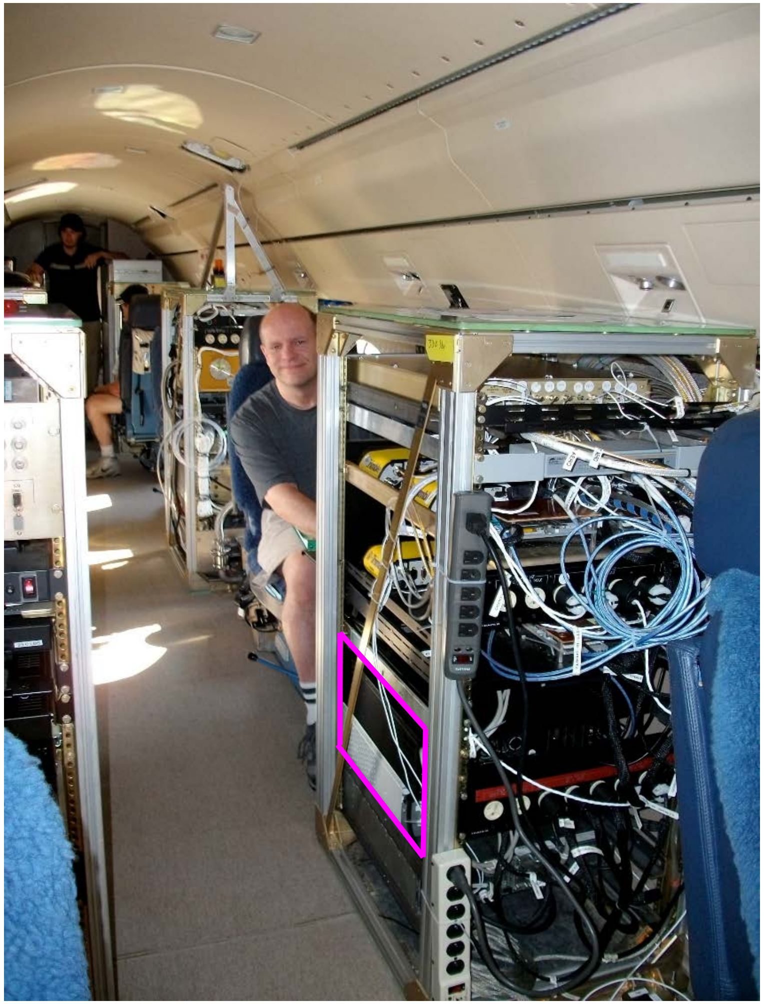
- GPS RO measurements are nearly weather free. Studies have shown that the assimilation of spaceborne GPS RO data can improve large-scale features.
- However, the coverage of the spaceborne GPS RO data are sparse for mesoscale applications. Thus a GPS RO receiver was placed on the NSF/NCAR GV aircraft during the PREDICT* field campaign in 2010 to collect denser GPS RO data for tropical cyclone studies.

** PREDICT: PRE-Depression Investigation of Cloud-systems in the Tropics*

Objective

- Investigate the impact of assimilating airborne GPS RO data on Hurricane Karl (2010) forecast using different observational operators.

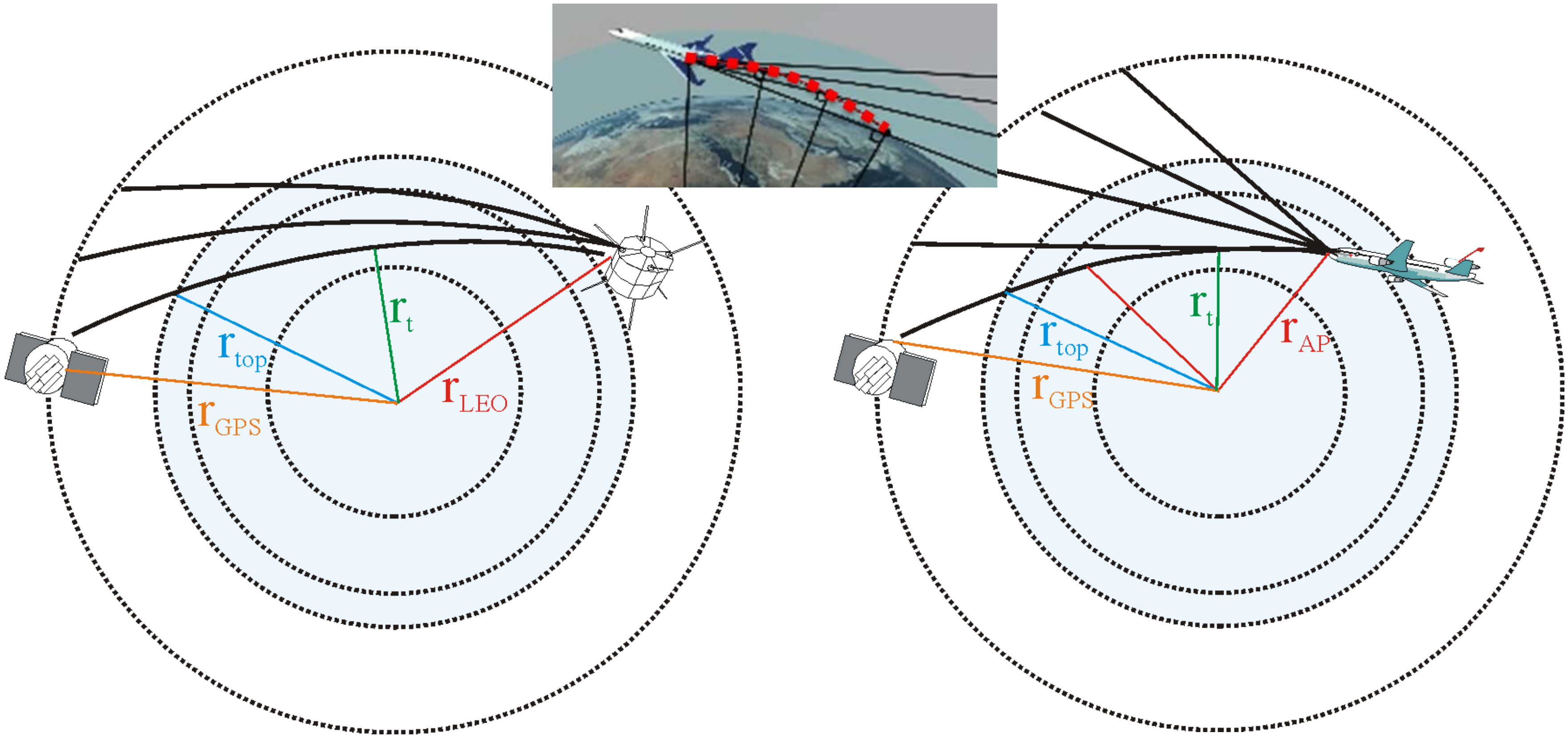
GISMOS Installed on NSF/NCAR GV



"*GISMOS*" (GNSS [Global Navigation Satellite System] Instrument System for Multistatic and Occultation Sensing)

Spaceborne (L) vs. Air-borne (R) GPS ROs

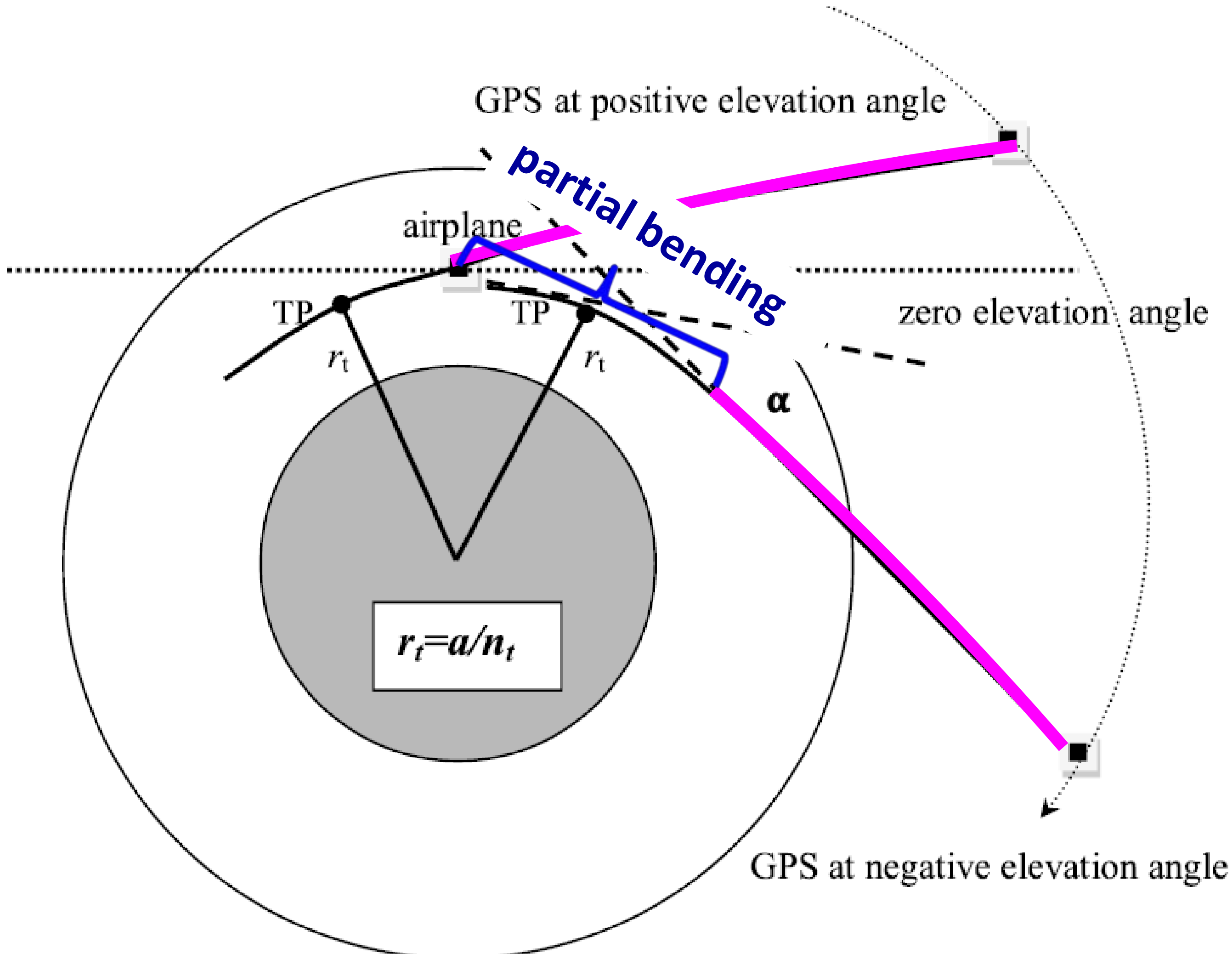
ARO's tangent points horizontally drift 2-3 times of SRO's



$$\alpha = 2\int_{r_t}^{r_{top}} \frac{1}{\sqrt{n^2r^2-a^2}}\frac{d(\ln n)}{dr}dr \qquad \alpha = \int_{r_t}^{r_{AP}} \frac{1}{\sqrt{n^2r^2-a^2}}\frac{d(\ln n)}{dr}dr + \int_{r_t}^{r_{top}} \frac{1}{\sqrt{n^2r^2-a^2}}\frac{d(\ln n)}{dr}dr$$

Airborne GPS ROs

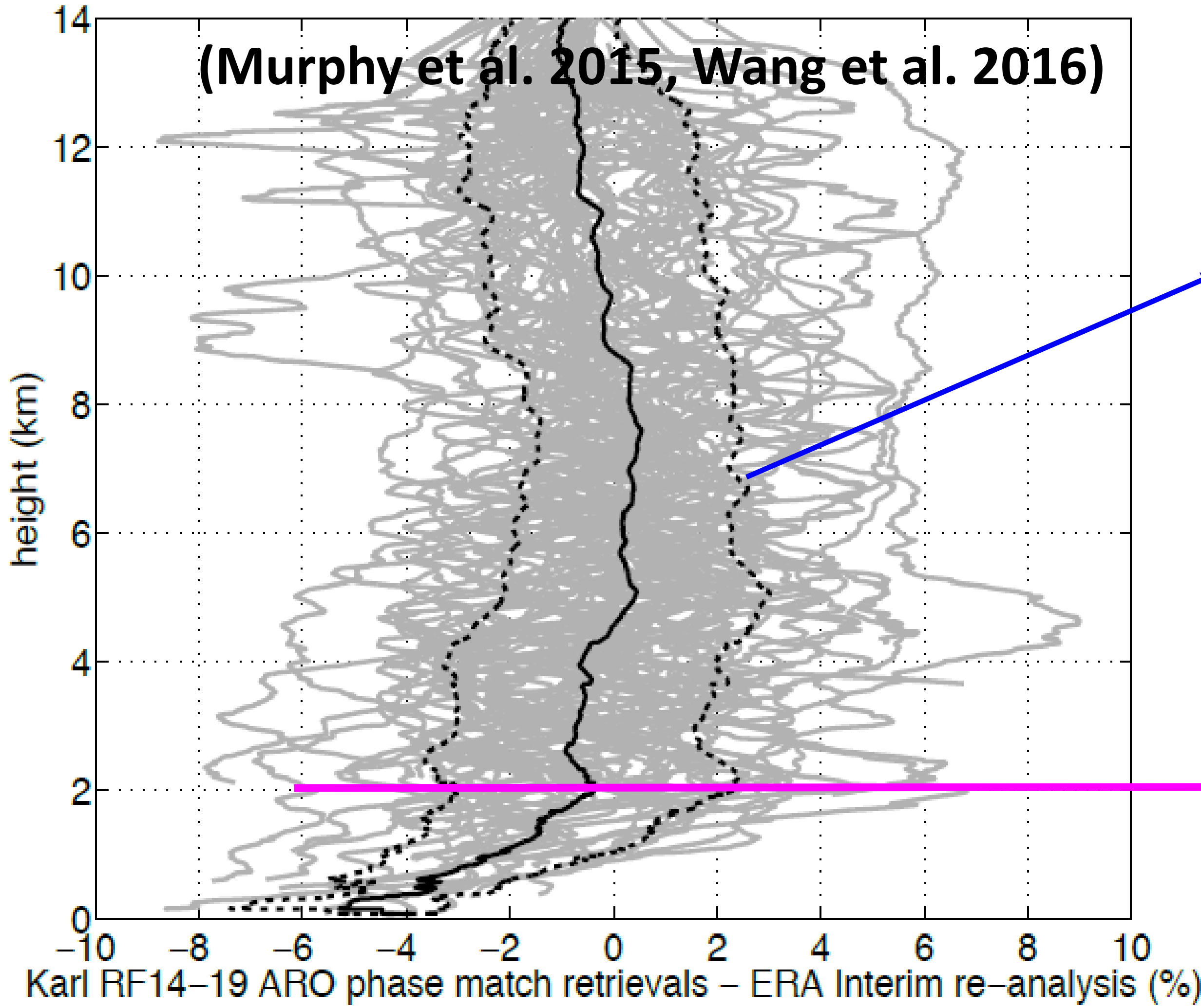
Removing the effect of the atmosphere above the airplane level



Murphy et al., 2015

ARO FSI Retrieval vs. ERA-Interim

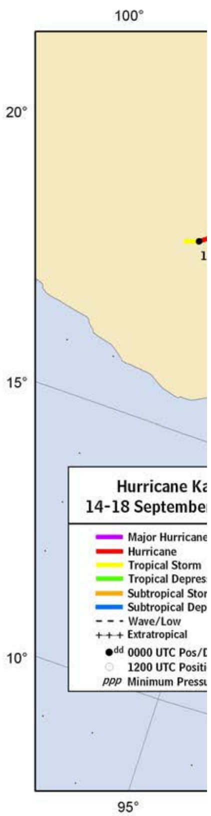
Retrievals from open–loop tracking and phase matching (PM)



~ 2% standard deviation in the difference between the retrieved ARO refractivity and the ERA-Interim reanalysis.

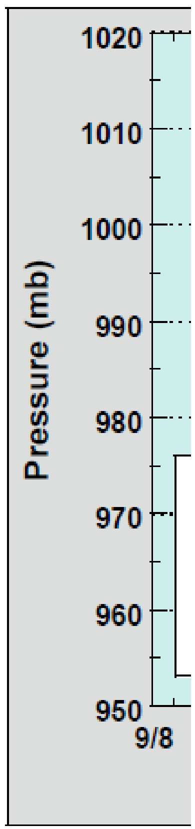
Apparent bias at low levels below 2km, possibly from multipath issues.
(Data are discarded in data assimilation.)

Case study: Hurricane Karl 2010



NHC/NOAA

Figure 3.



Selected pr
2010. Adva
observation

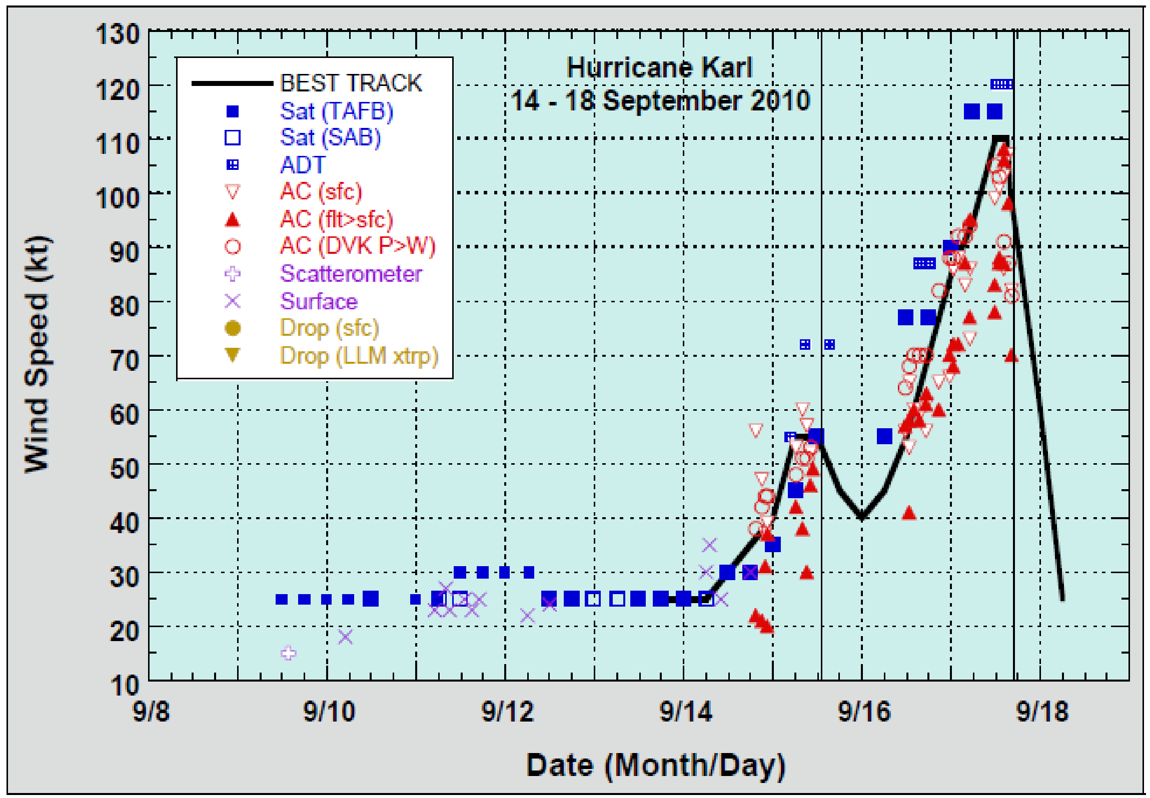
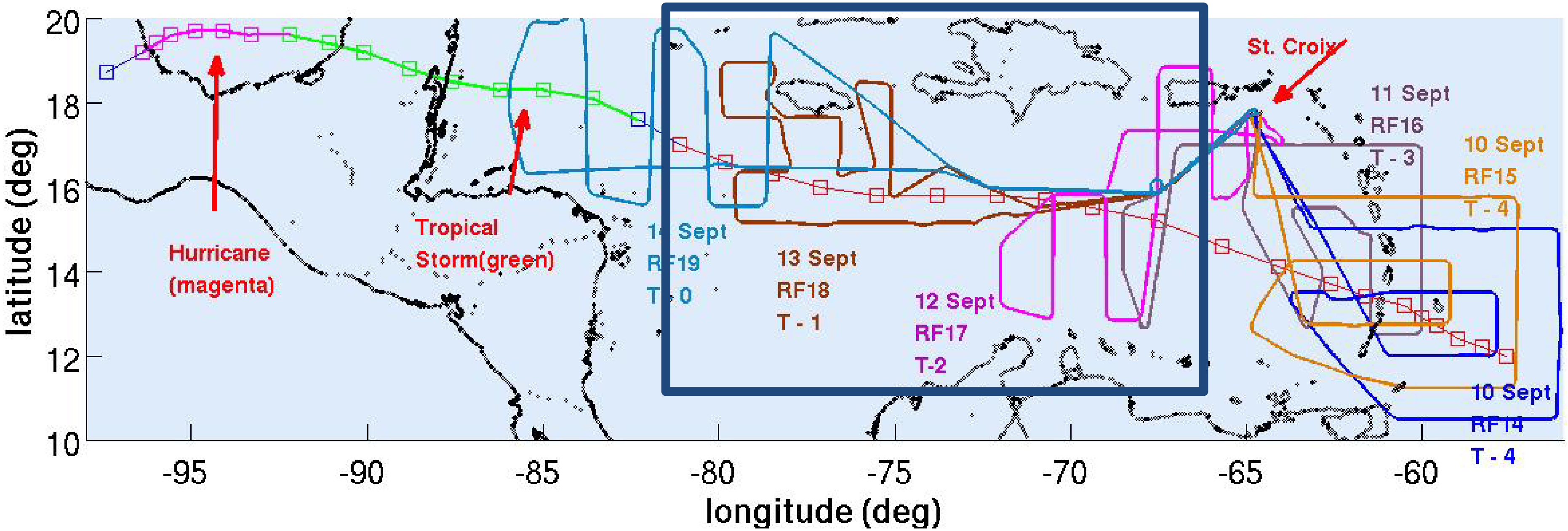


Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Karl, 14-18 September 2010. Aircraft observations have been adjusted for elevation using 90%, 80%, and 80% adjustment factors for observations from 700 mb, 850 mb, and 1500 ft, respectively. Advanced Dvorak Technique estimates represent linear averages over a two-hour period centered on the nominal observation time. Dashed vertical lines correspond to 0000 UTC. Solid vertical lines correspond to landfall times.

Case study: Hurricane Karl 2010

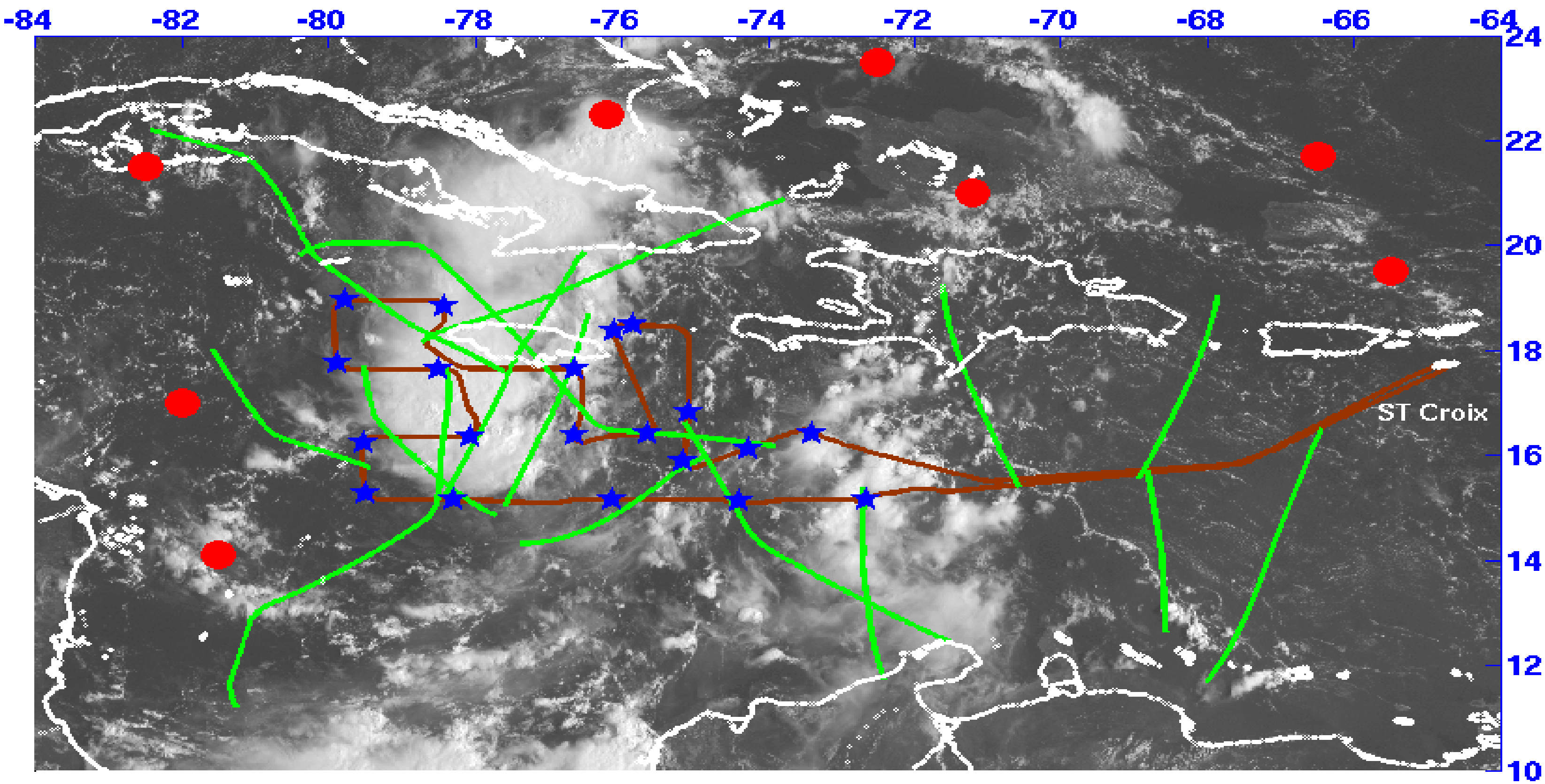
6 flights into pre-Hurricane Karl



Flight RF18 (Sep 13): ~1 day before Karl genesis

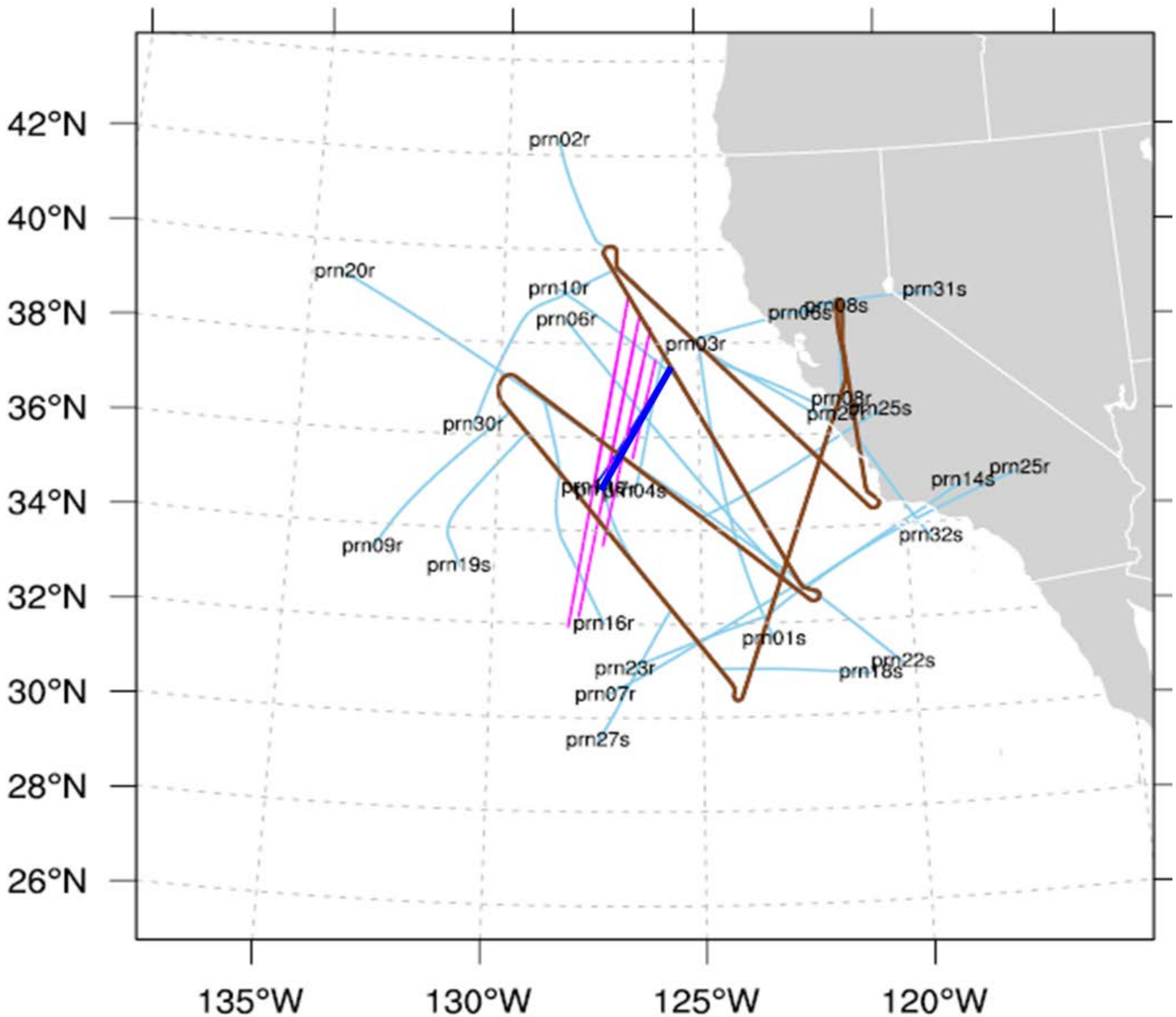
PREDICT – Airborne GPS RO vs COSMIC

COSMIC ARO Dropsonde

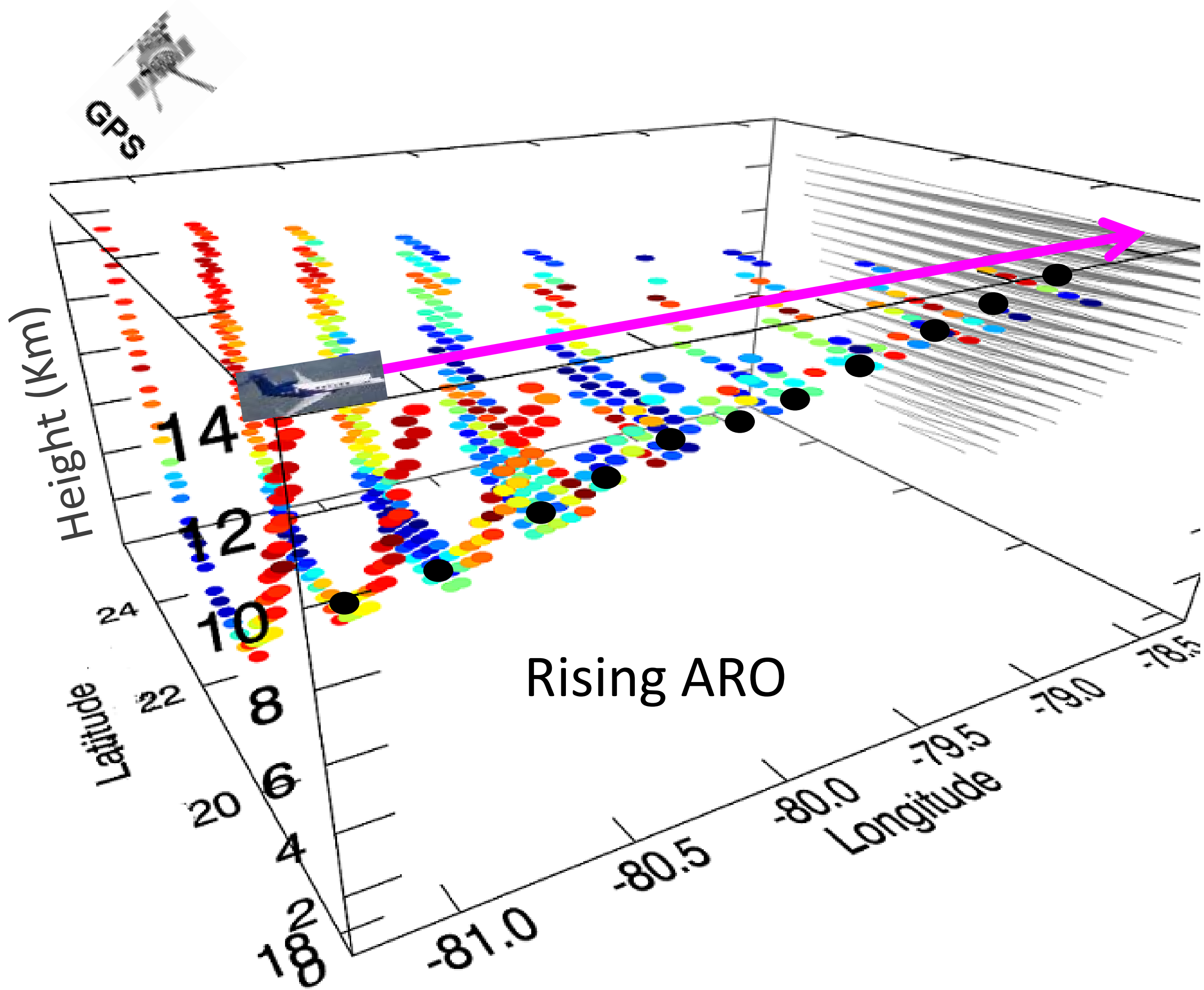


Flight RF18 (Sep 13): ~1 day before Karl genesis

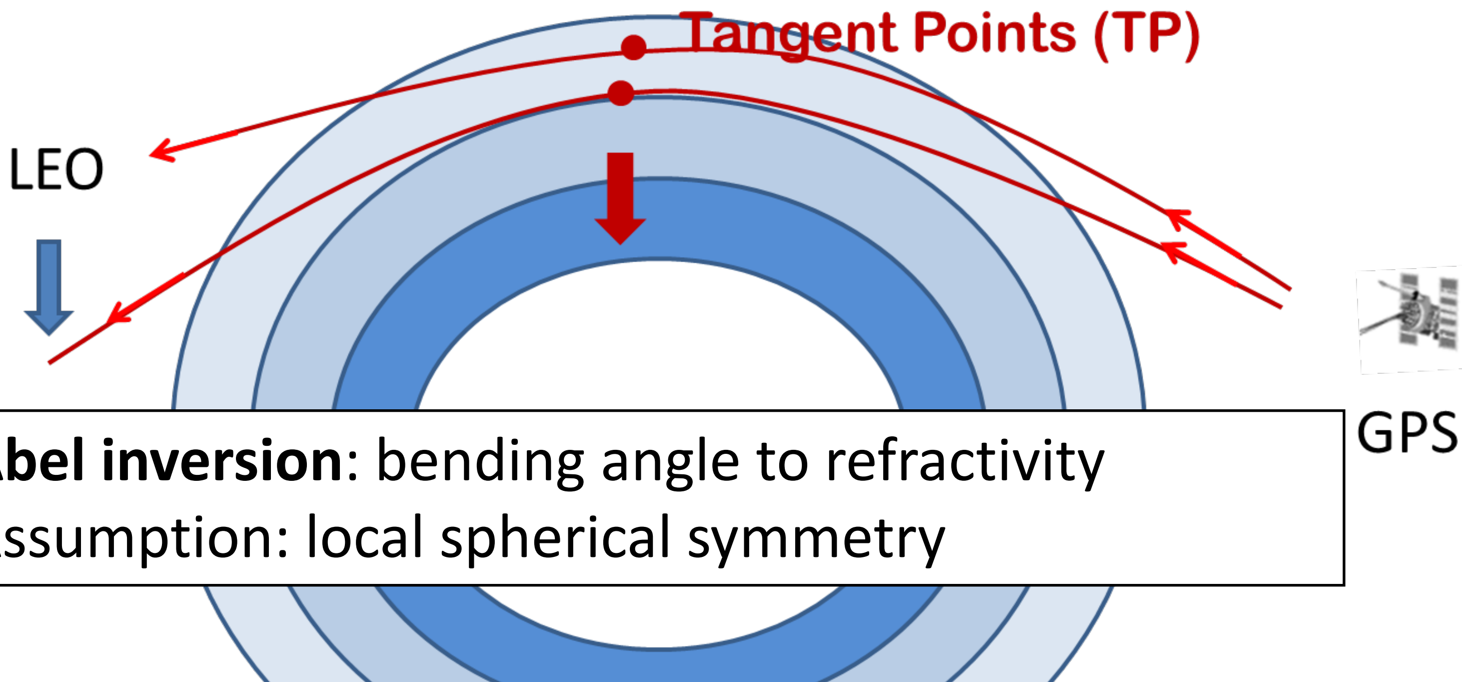
Airborne GPS RO Rays



Data: Refractivity vs. Excess Phase



Data: Refractivity vs. Excess Phase



Abel inversion: bending angle to refractivity

Assumption: local spherical symmetry

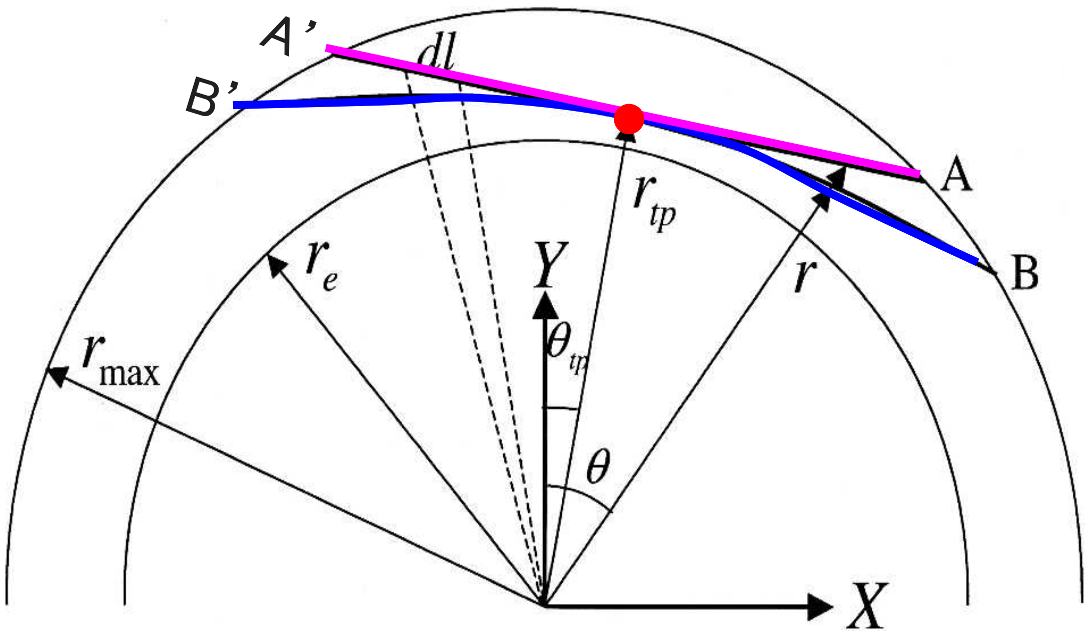
How are we going to use the data after knowing their basic characteristics?

Observable = phase data ➡ Doppler shift ➡ bending angle ➡ refractivity

Data: Refractivity vs. Excess Phase

Non-Local Operator
(Excess phase)

$$EPH \approx \int_{A'}^{A} N\, ds$$

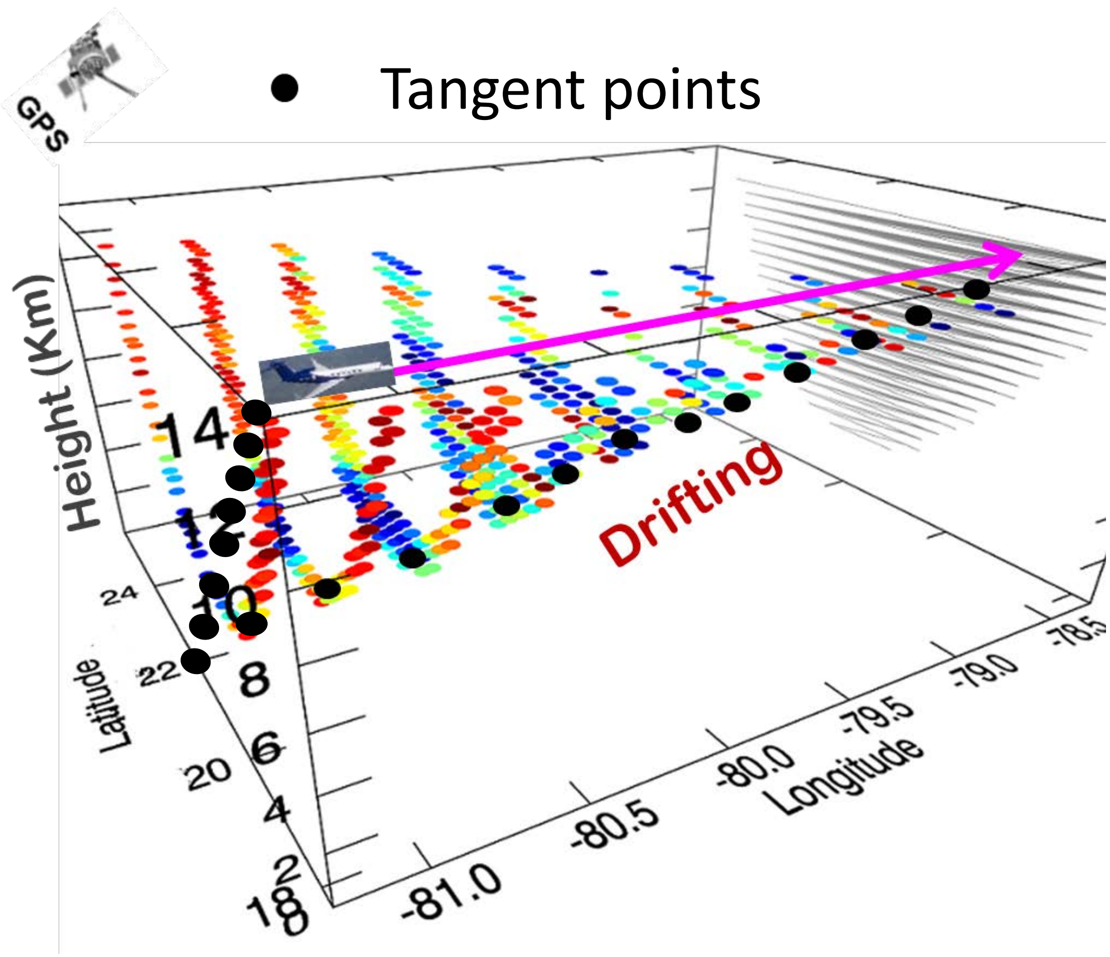


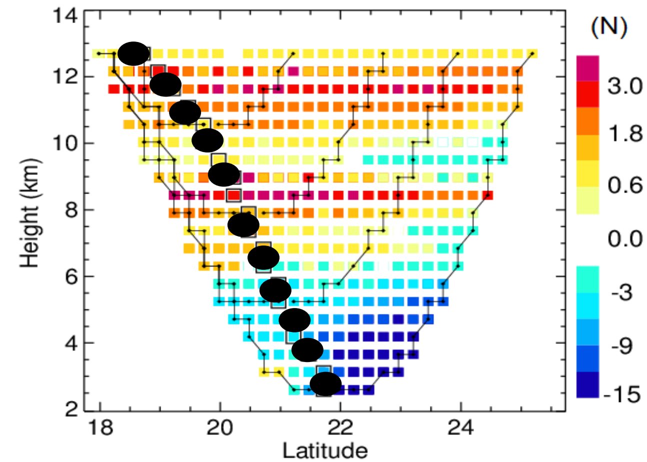
Local operator
(Refractivity)

$$N \approx 77.6\frac{P}{T} + 3.73\times 10^{5}\frac{P_w}{T^2}$$

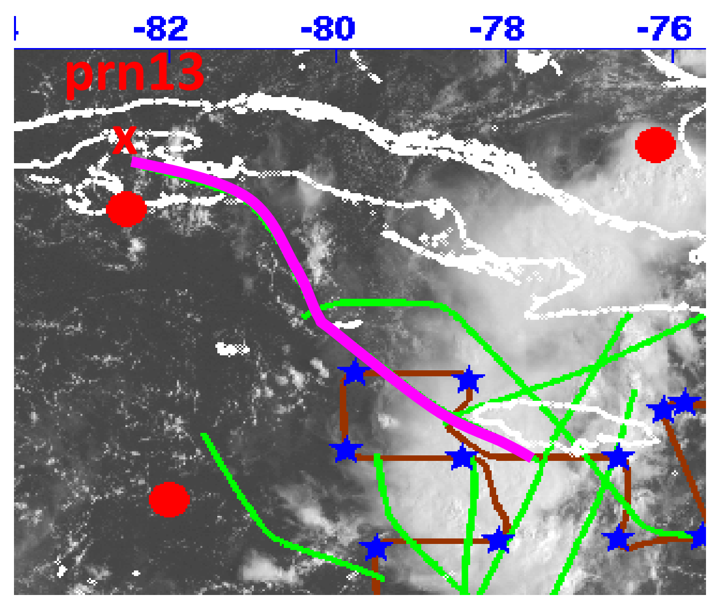
Sokolovskiy et al. 2005

Drifting vs. Non-Drifting Tangent Points

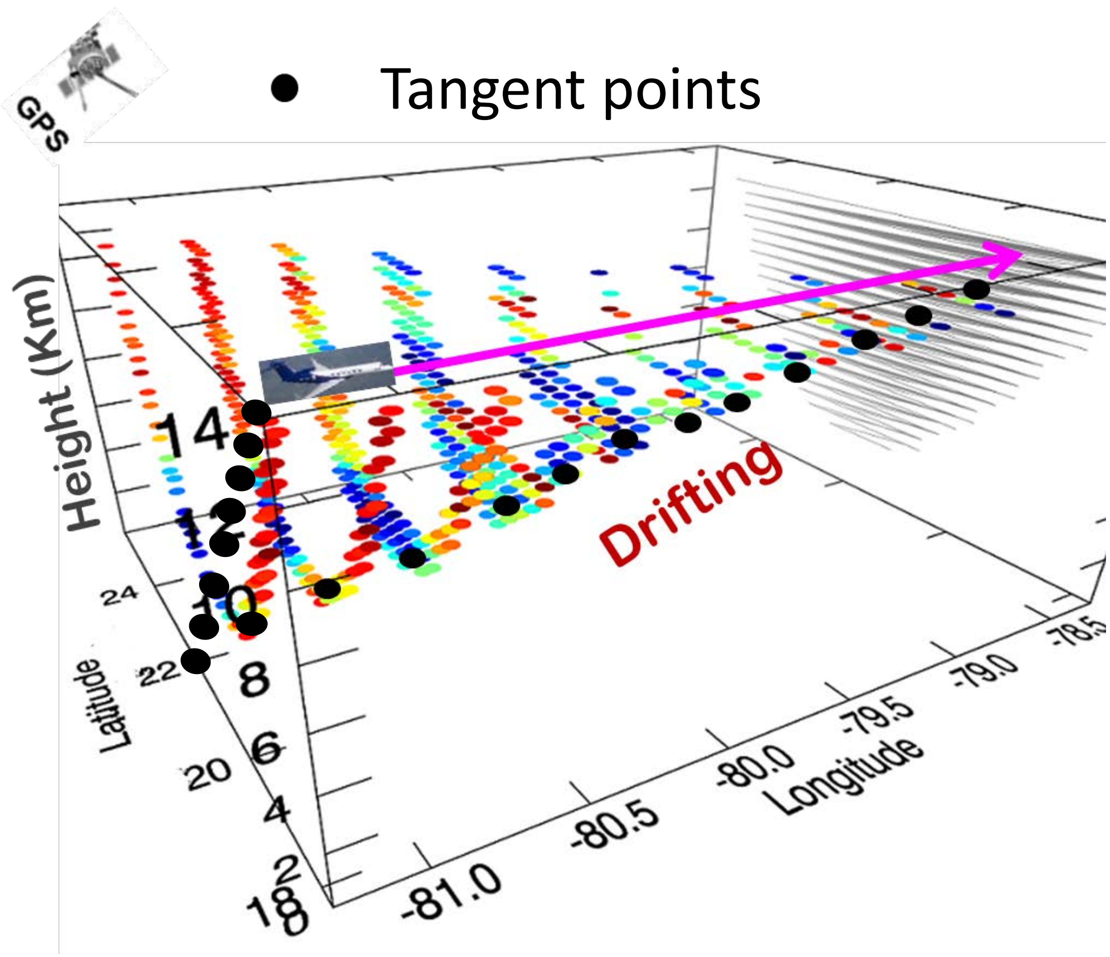


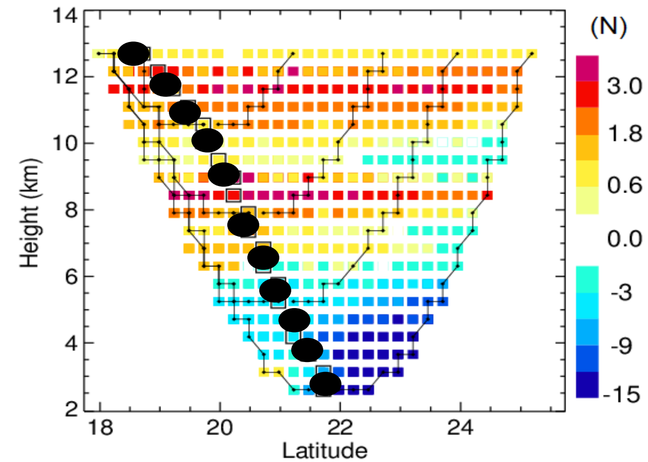


Drifting (projected to a 2D plane)

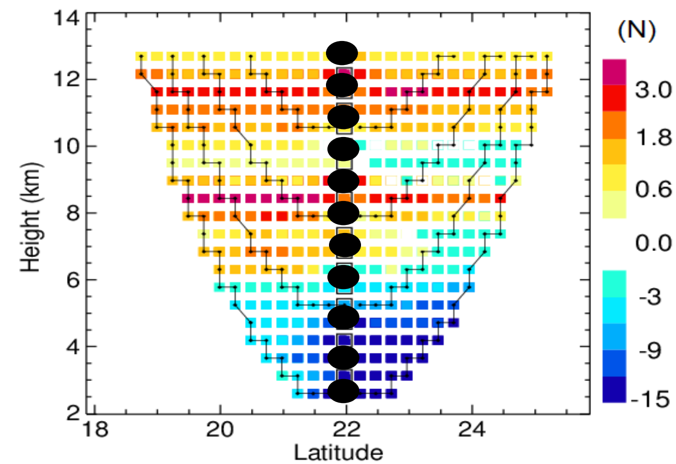


Drifting vs. Non-Drifting Tangent Points



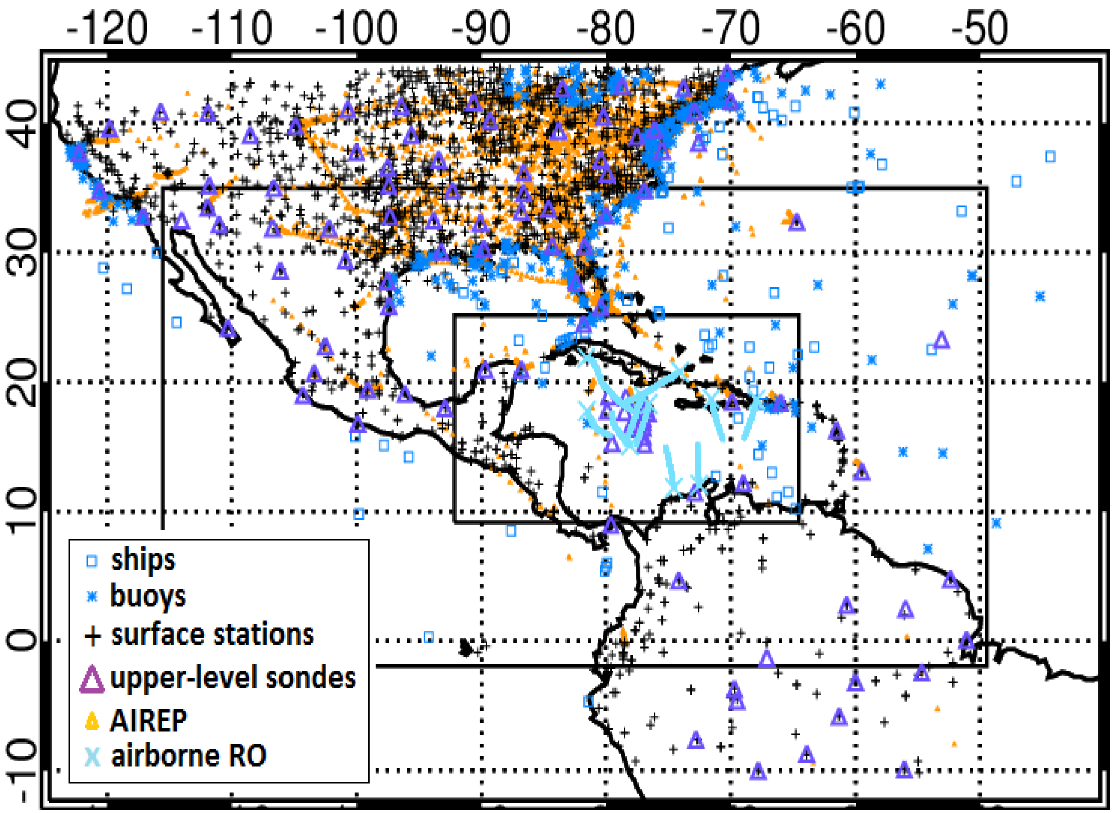


Drifting (projected to a 2D plane)



Non-drifting

Numerical Experiments

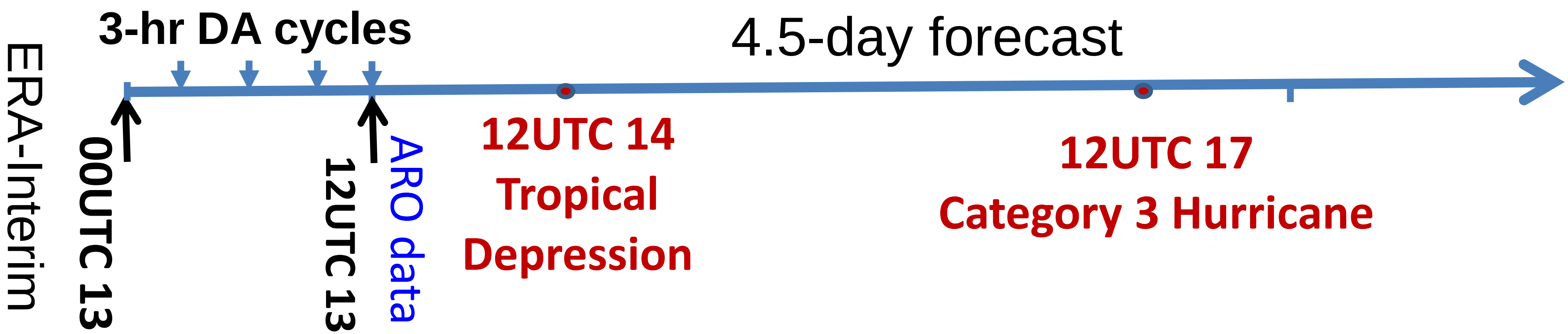


Resolution: 27, 9, 3km Vortex following	
Microphysics	Morrison
PBL	YSU
Cumulus (d01, d02)	Kain-Fritsch
Longwave	RRTM
Shortwave	Goddard

WRFV3.2, WRF 3DVAR with modified GPSRO operator for airborne receiver, based on the one for spaceborne (Chen et al. 2009).

BE: 60 pairs of 12 and 24-hr WRF forecast differences (NMC-method).

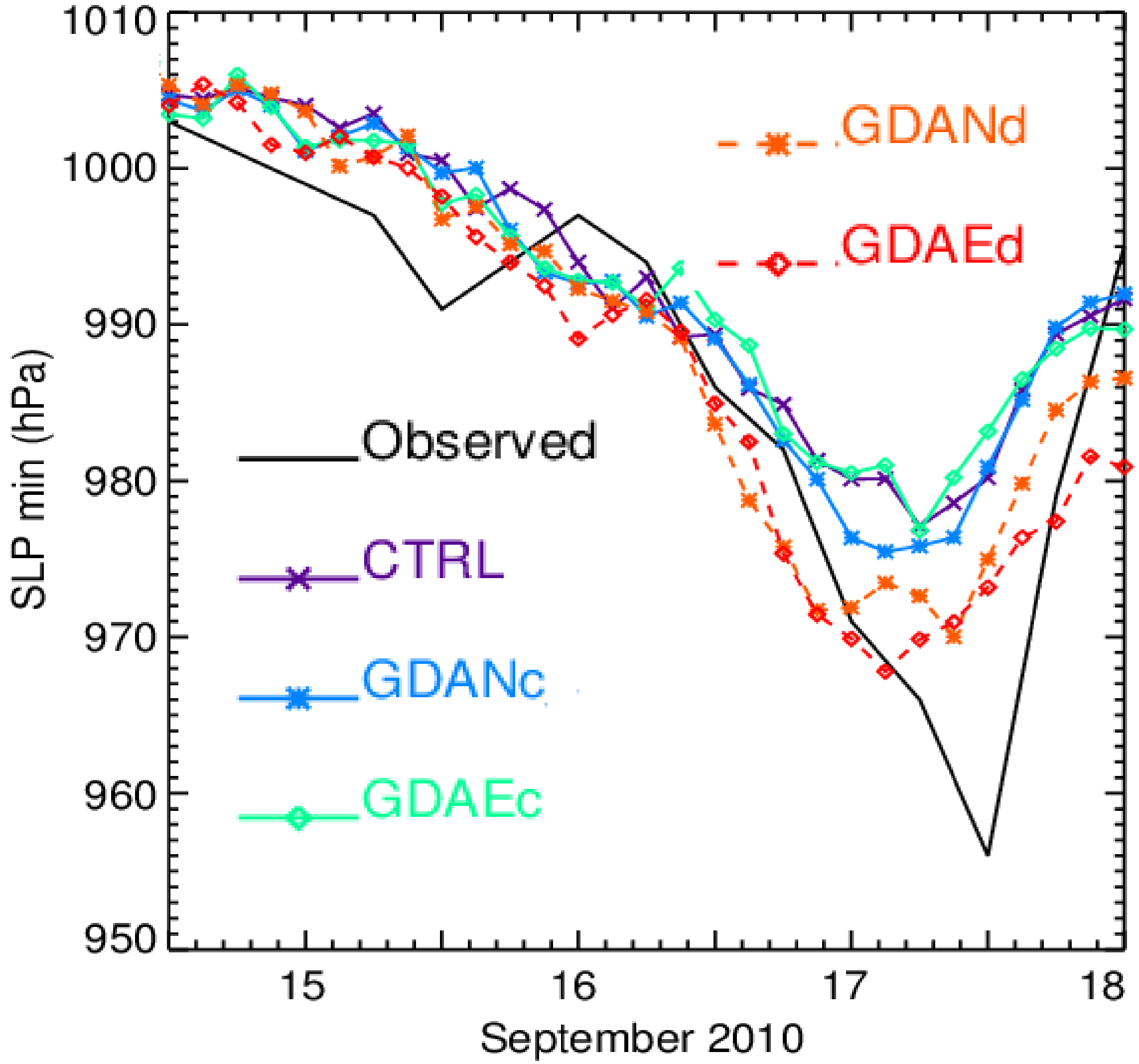
Numerical Experiments



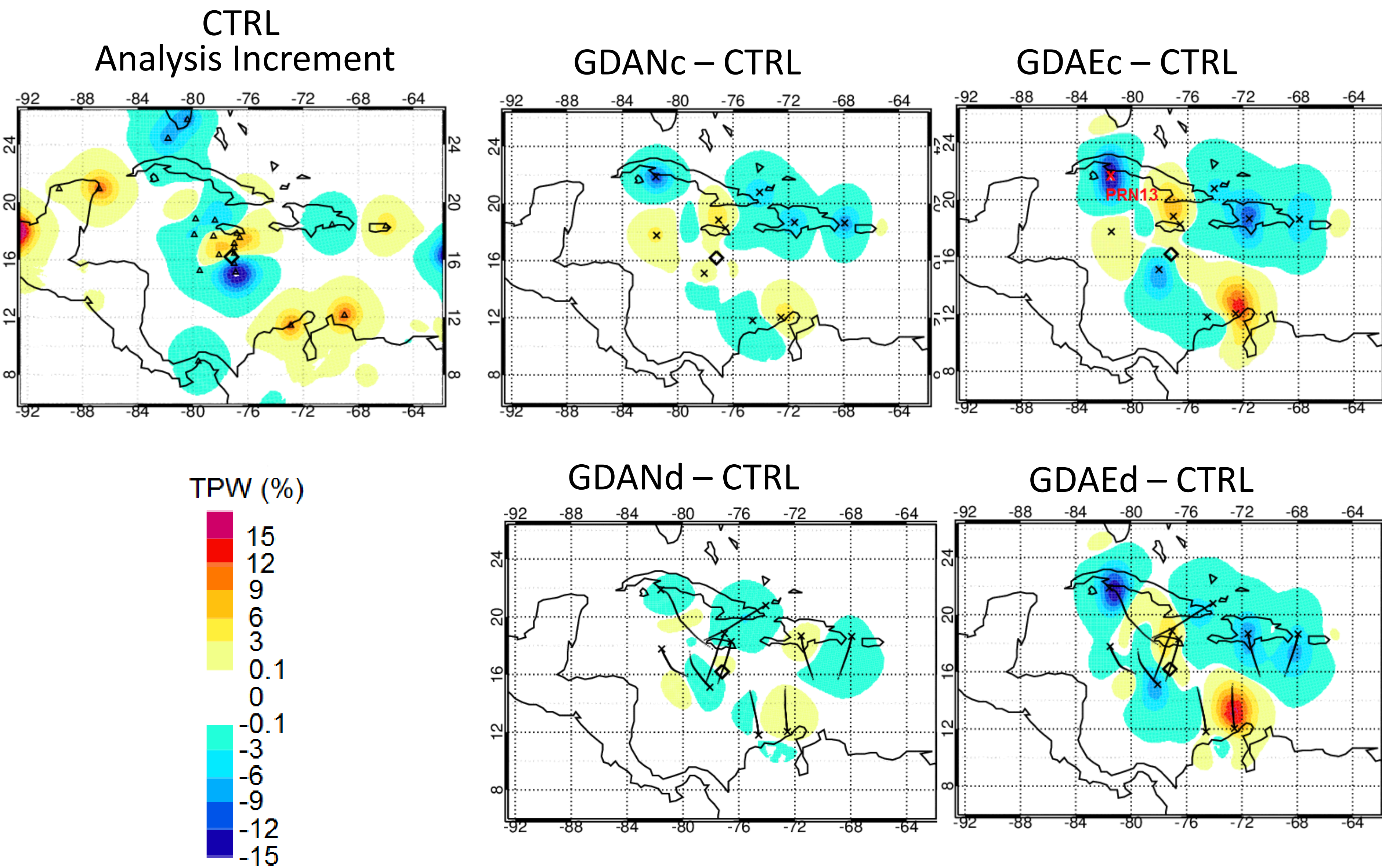
Exp.	*Observations assimilated*
CTRL	GTS + dropsondes
GDANc	CNTL data + ARO local refractivity with no drifting of tangent points (i.e. column data), 2% error
GDANd	Same as GDANc, except with drifting tangent points
GDAEc	CNTL data + ARO excess phase with column data, 1% error
GDAEd	Same as GDAEc, except with drifting tangent points

Intensity Forecast (Min SLP)

1200 UTC 14 Sept. – 0000 UTC 18 Sept. 2010

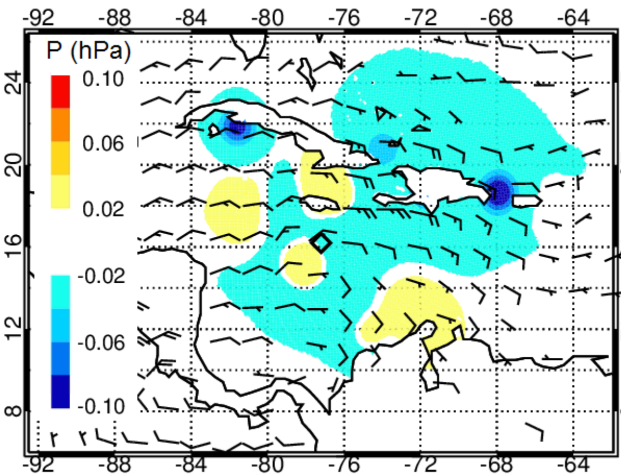


TPW Analysis Differences (12Z Sep 13)

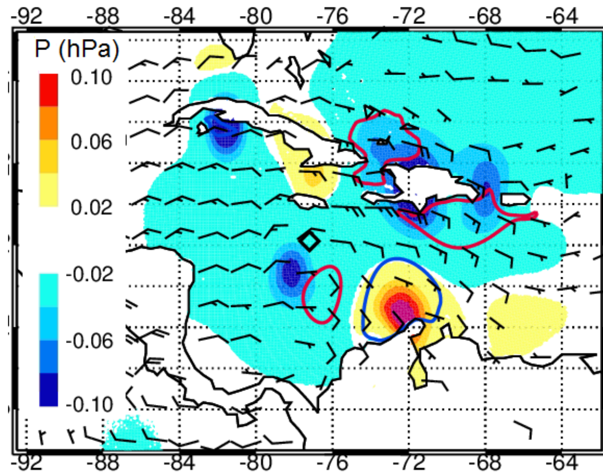


Analysis Differences @ 3 km

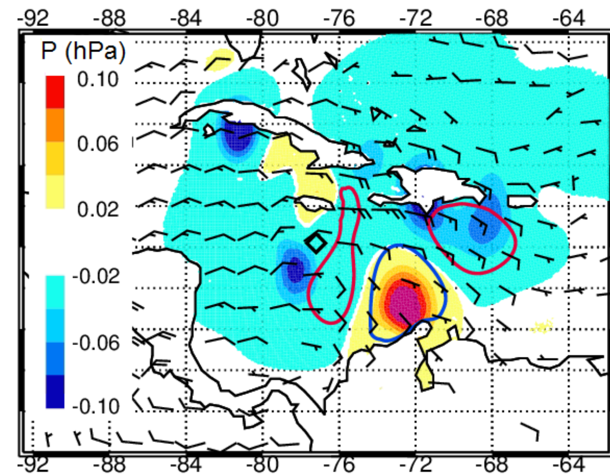
GDANc – CTRL, P, vor



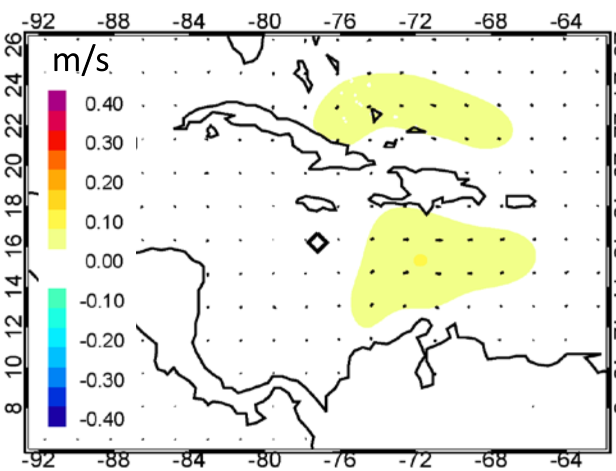
GDAEc – CTRL, P, vor



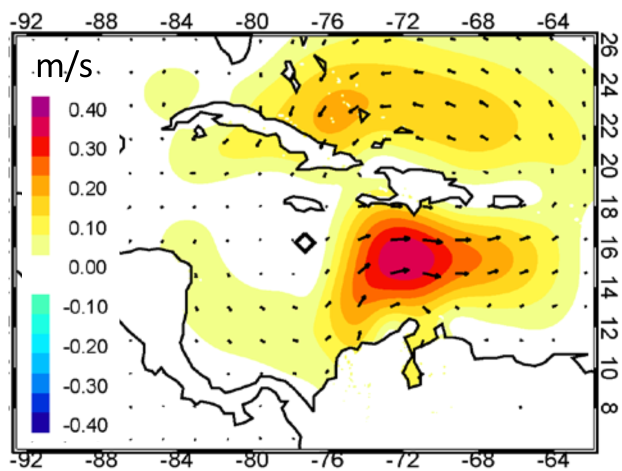
GDAEd – CTRL) P, vor



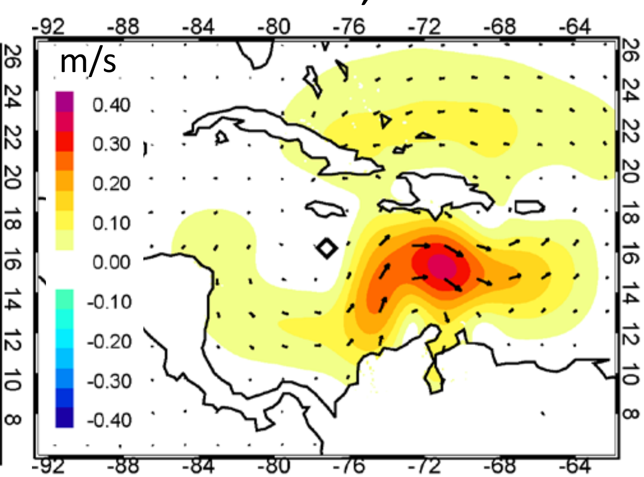
GDANc – CTRL, wind



GDAEc – CTRL, wind

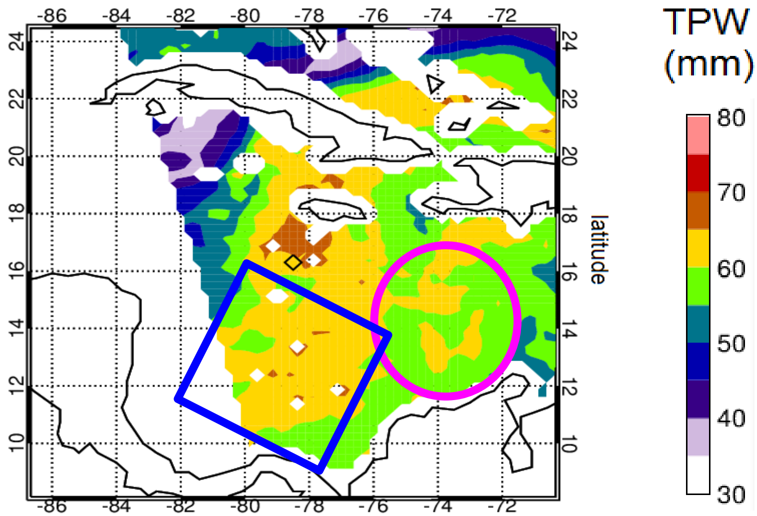


GDAEd – CTRL, wind



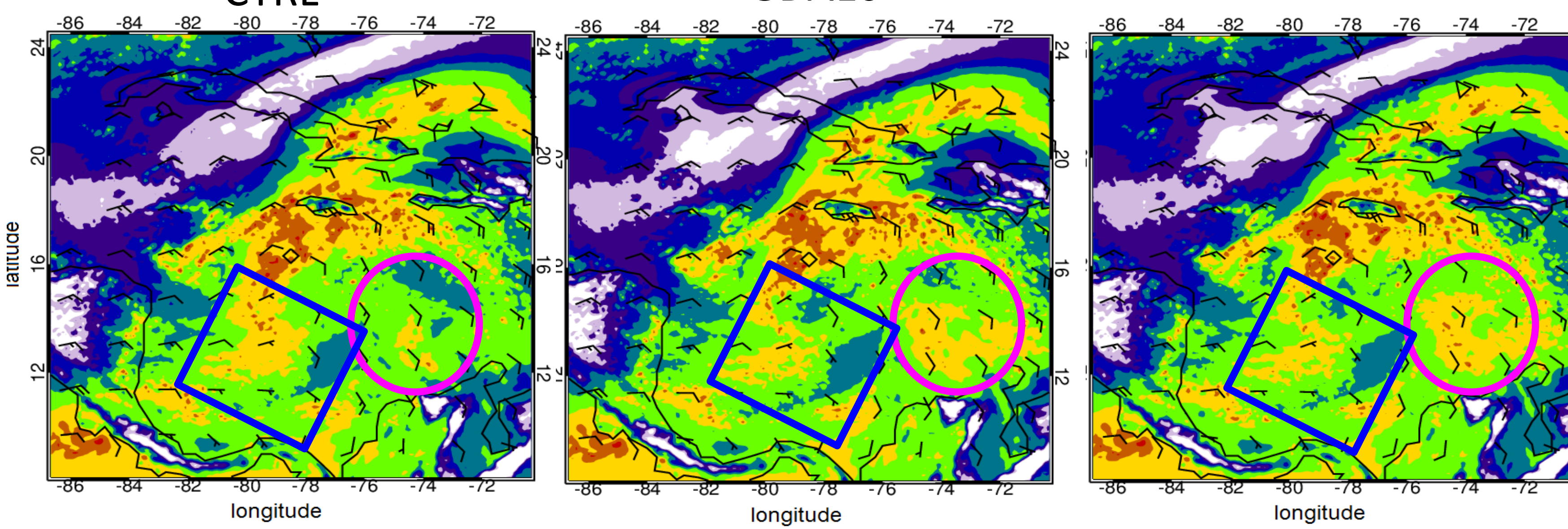
6-h TPW Forecasts (18Z 13 Sep.)

Composite Satellite Data



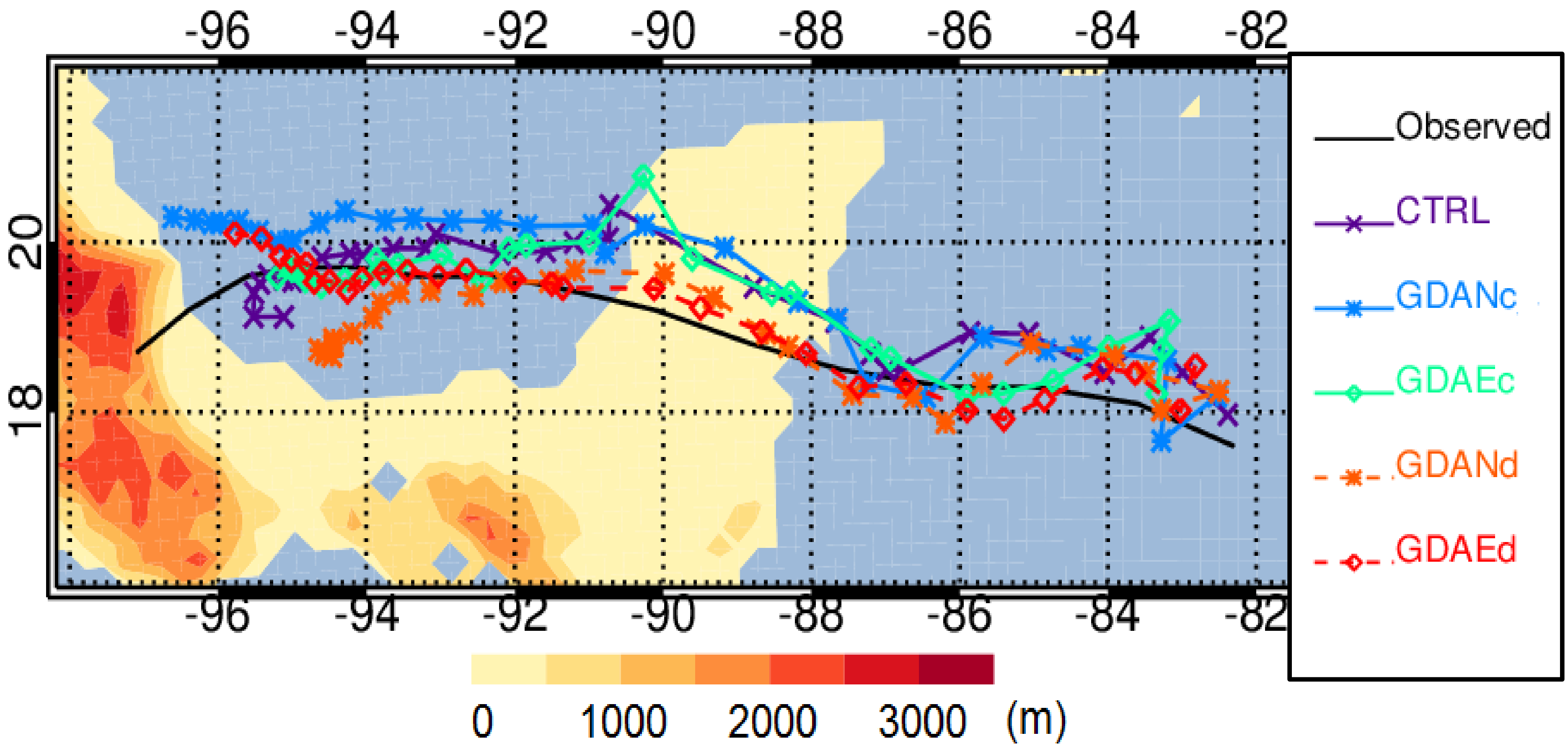
Torn and Cook (2013) found that the 48-h forecasts of Karl were particularly sensitive to initial mid-level moisture perturbations southeast of the storm north of Colombia and Venezuela.

CTRL GDAEc GDAEd



Track Forecasts

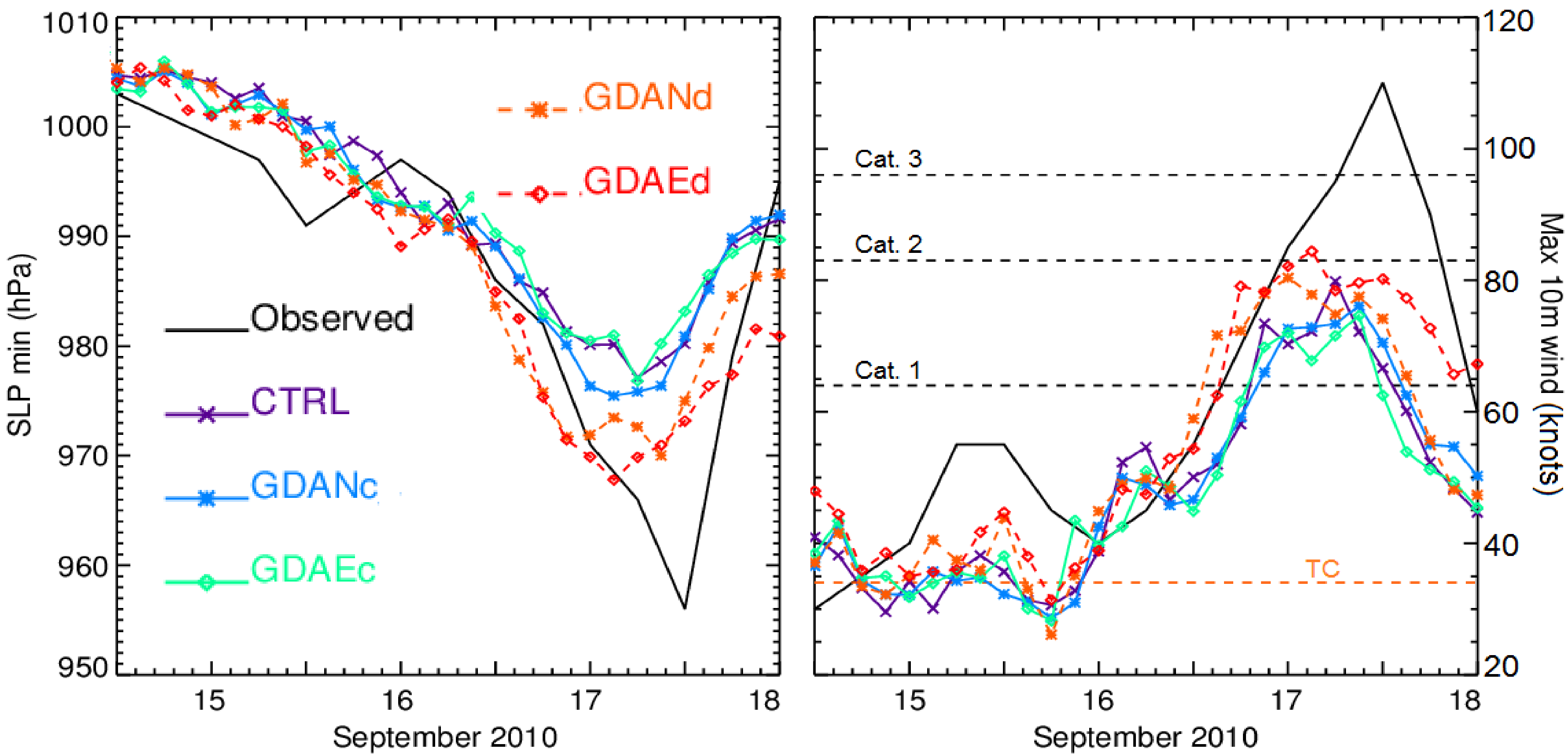
1200 UTC 14 Sept. – 0000 UTC 18 Sept. 2010



Intensity Forecasts

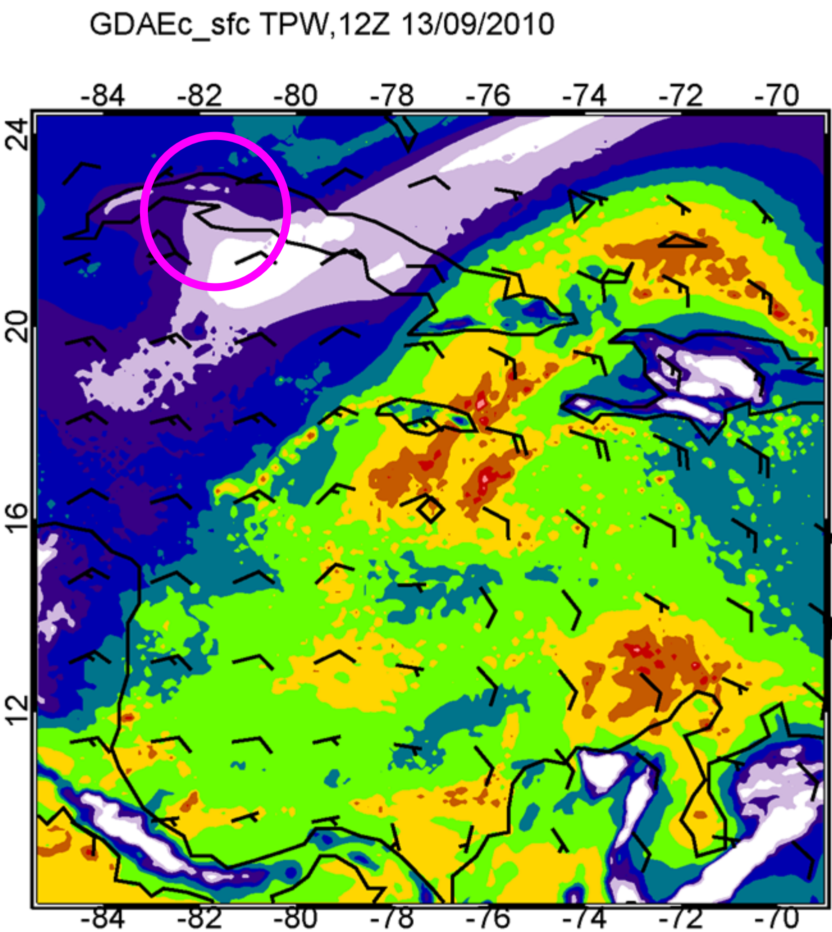
1200 UTC 14 Sept. – 0000 UTC 18 Sept. 2010

Min SLP	10-m wind speed

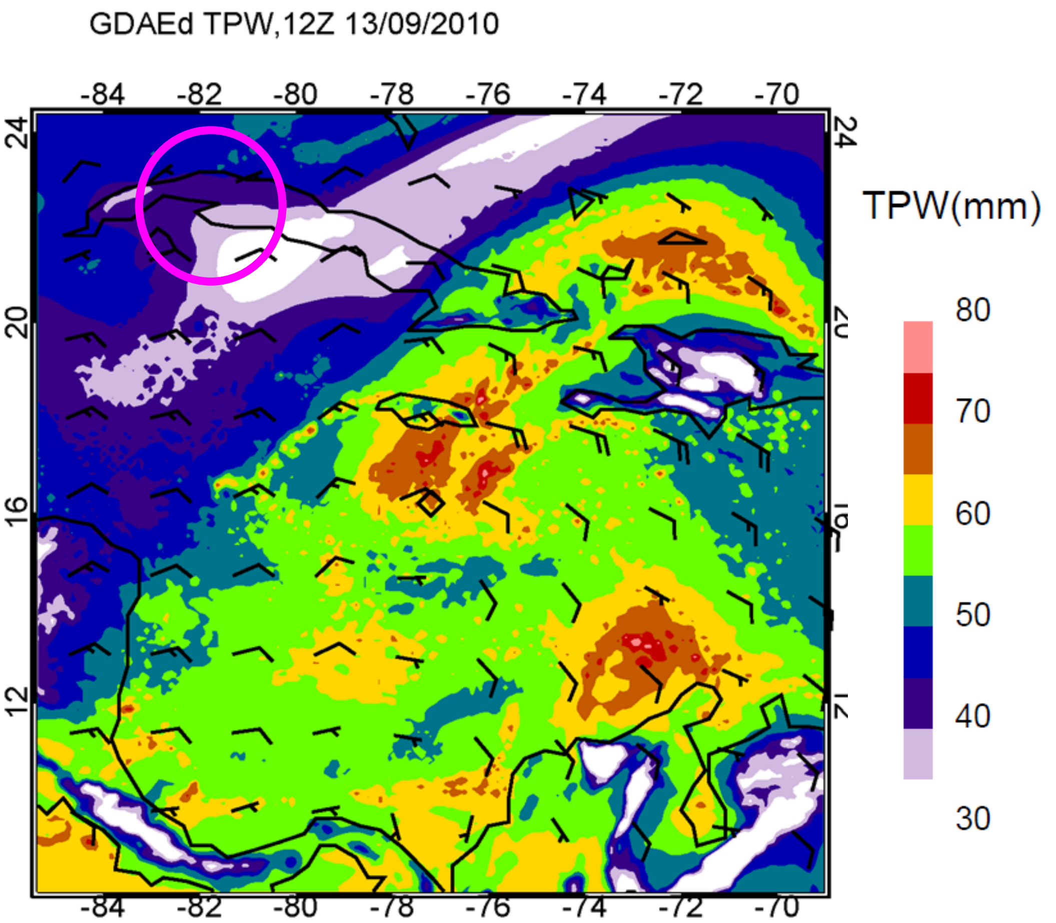


TPW Analysis (12Z 13 Sep.)

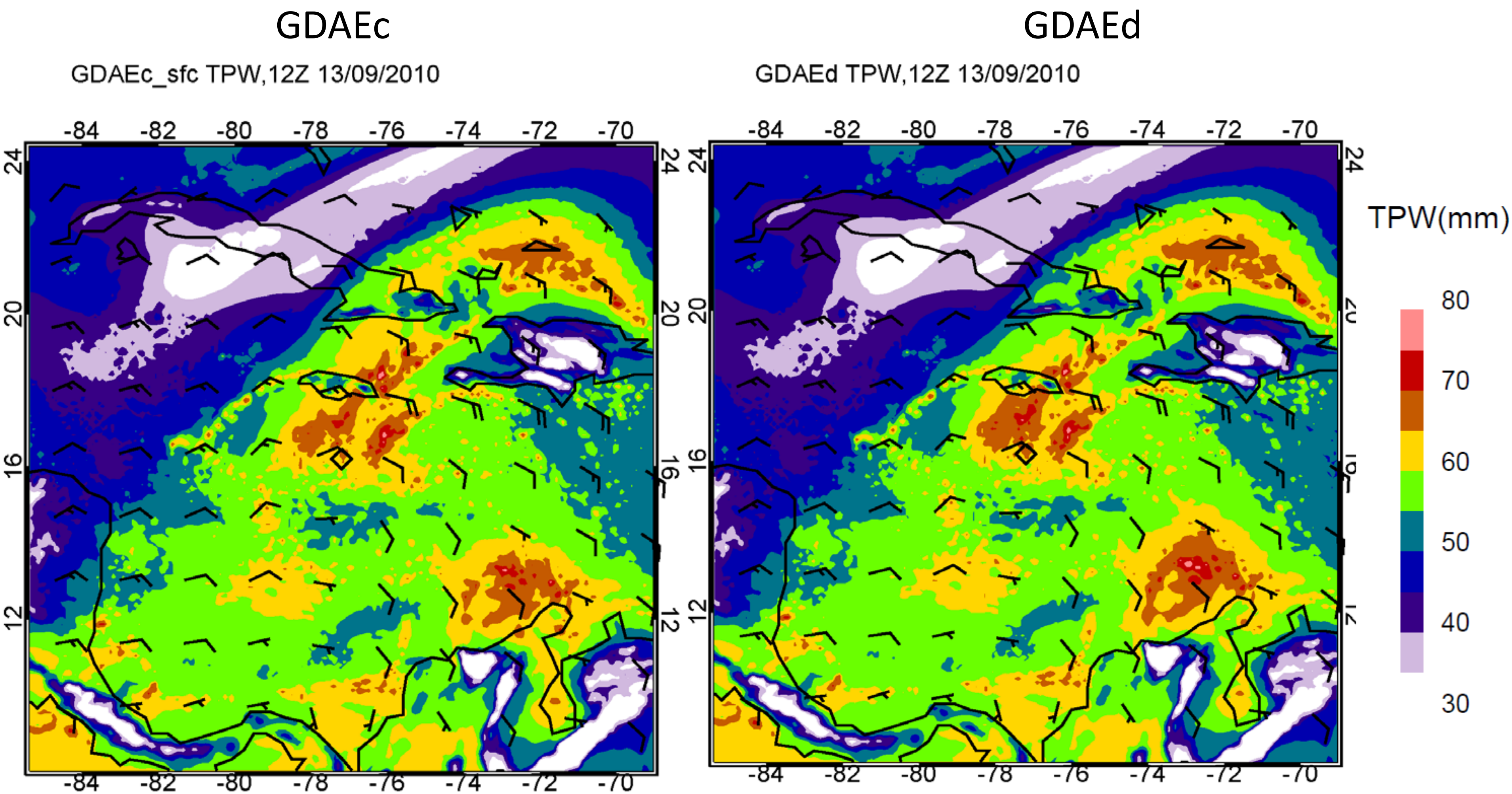
GDAEc



GDAEd



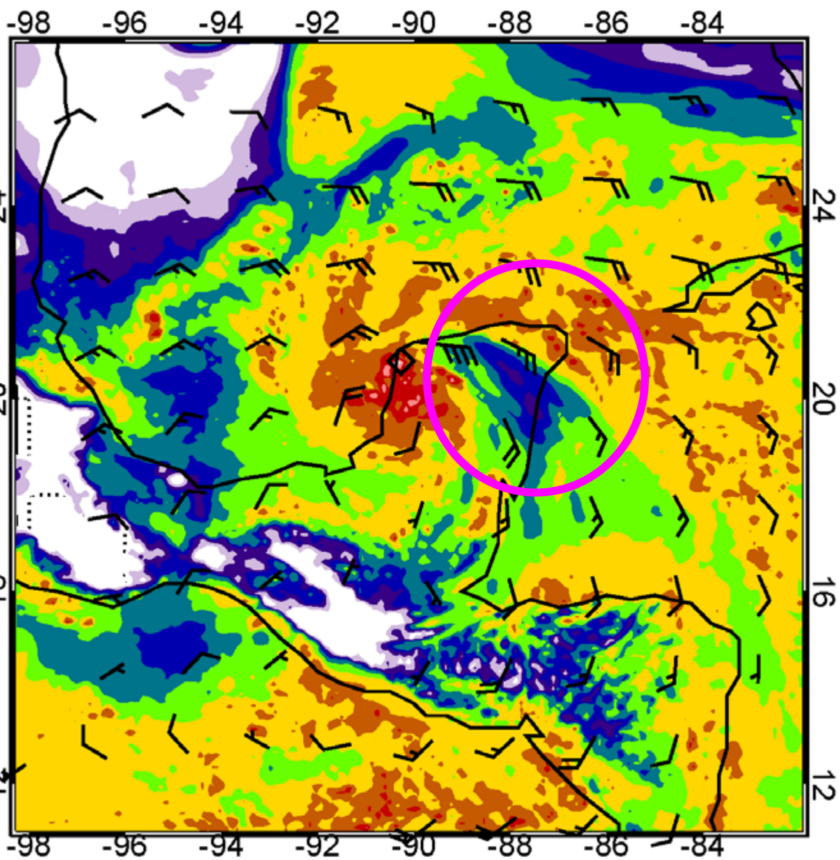
TPW Analysis (12Z 13 Sep.)



TPW (00Z 16 Sep)

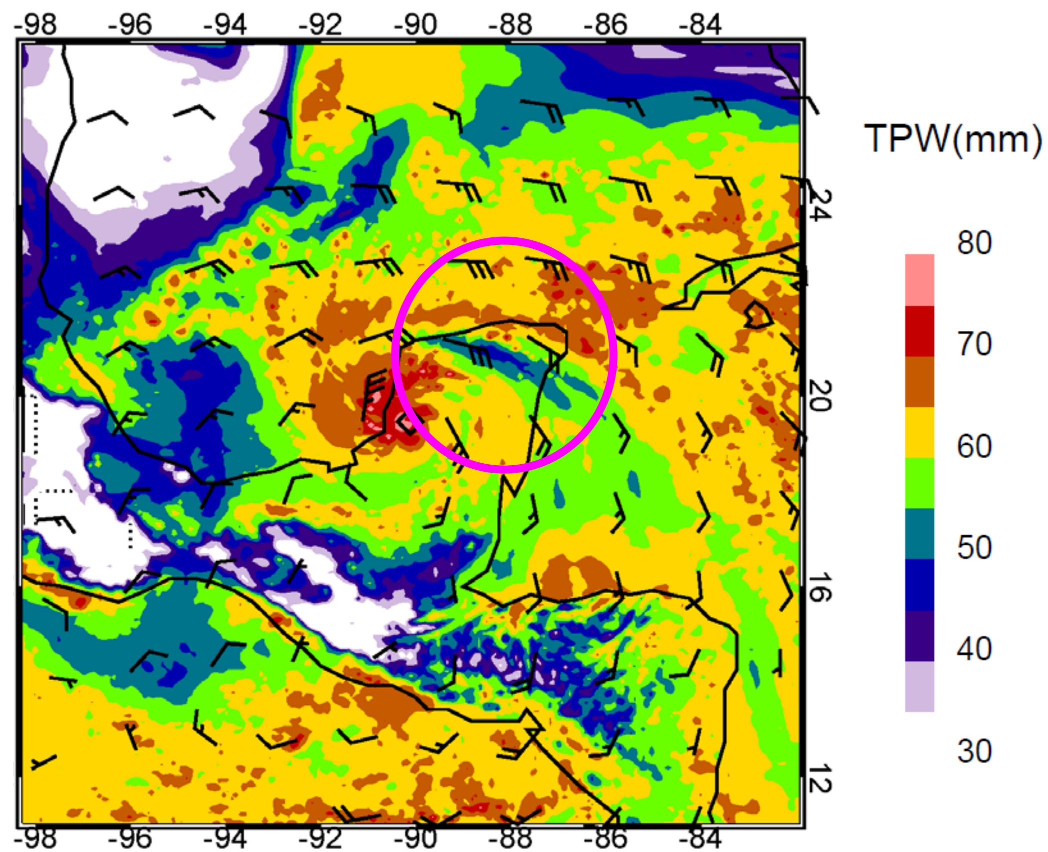
GDAEc

GDAEc_sfc TPW,00Z 16/09/2010

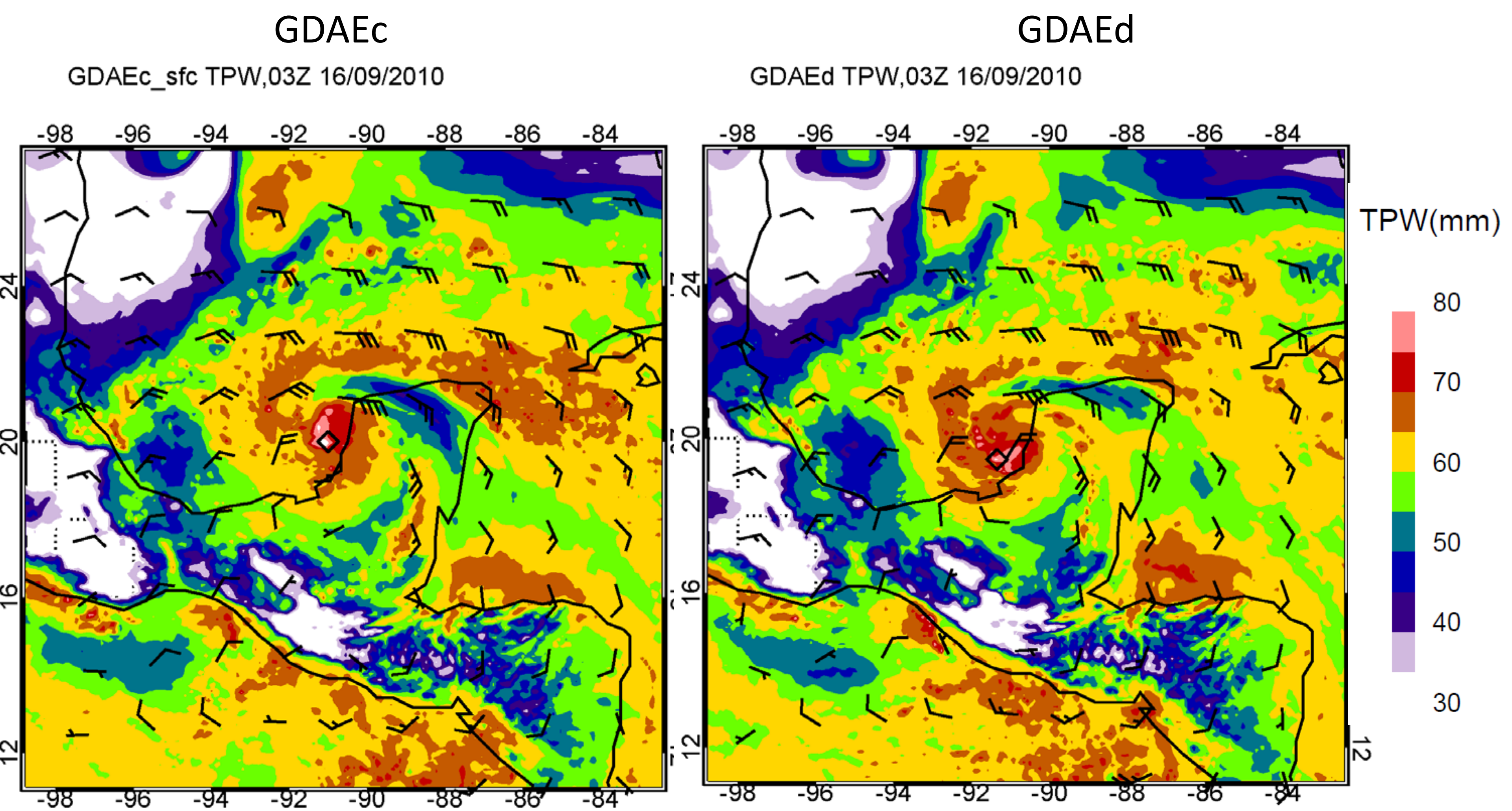


GDAEd

GDAEd TPW,00Z 16/09/2010

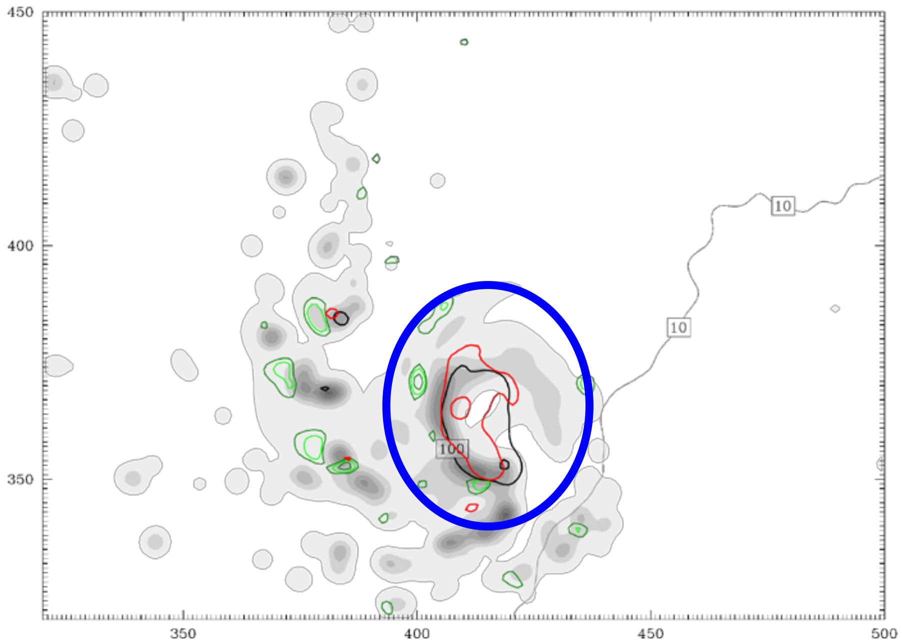


TPW (03Z 16 Sep)



Diabatic Cooling (Color Contours)

GDAEc 06Z Sep 16, 850 mb GDAEd

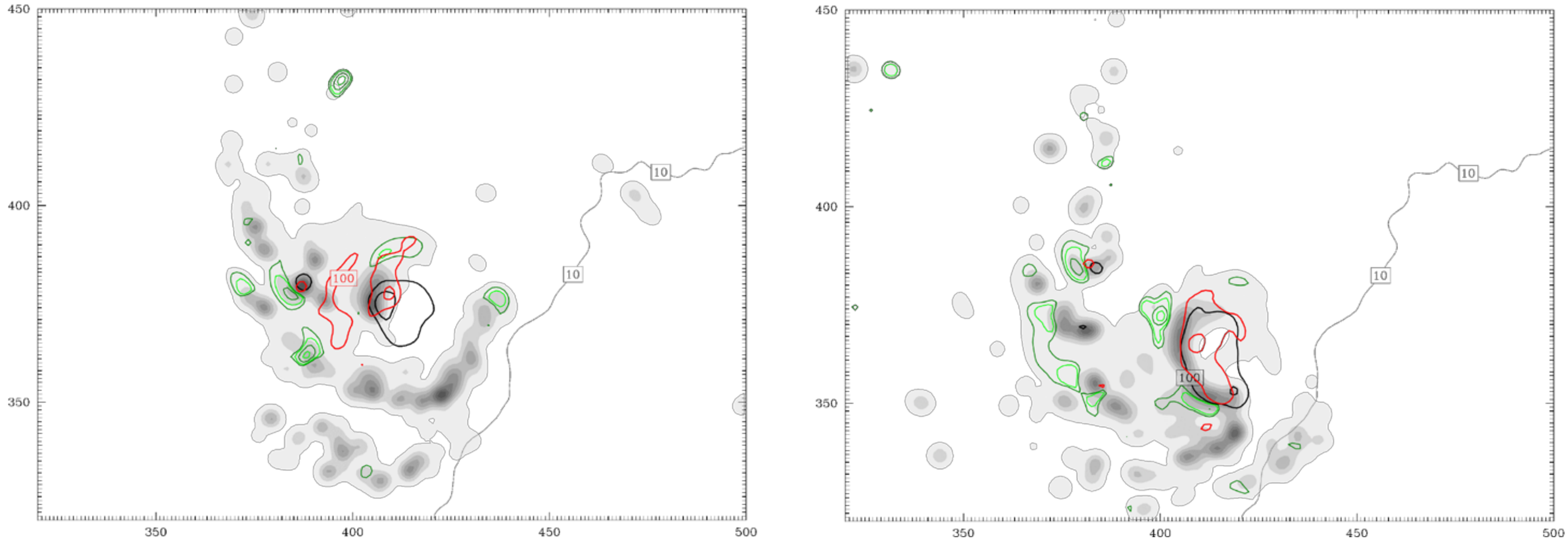


850 mb relative vorticity

500 mb relative vorticity

Diabatic Cooling (Color Contours)

GDAEc 06Z Sep 16, 800 mb GDAEd

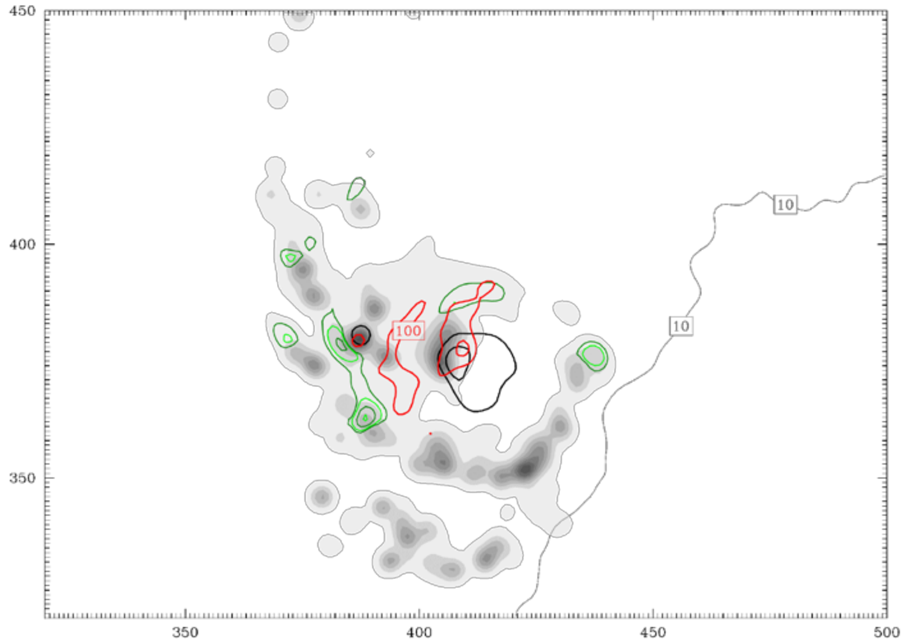


850 mb relative vorticity

500 mb relative vorticity

Diabatic Cooling (Color Contours)

GDAEc 06Z Sep 16, 750 mb GDAEd

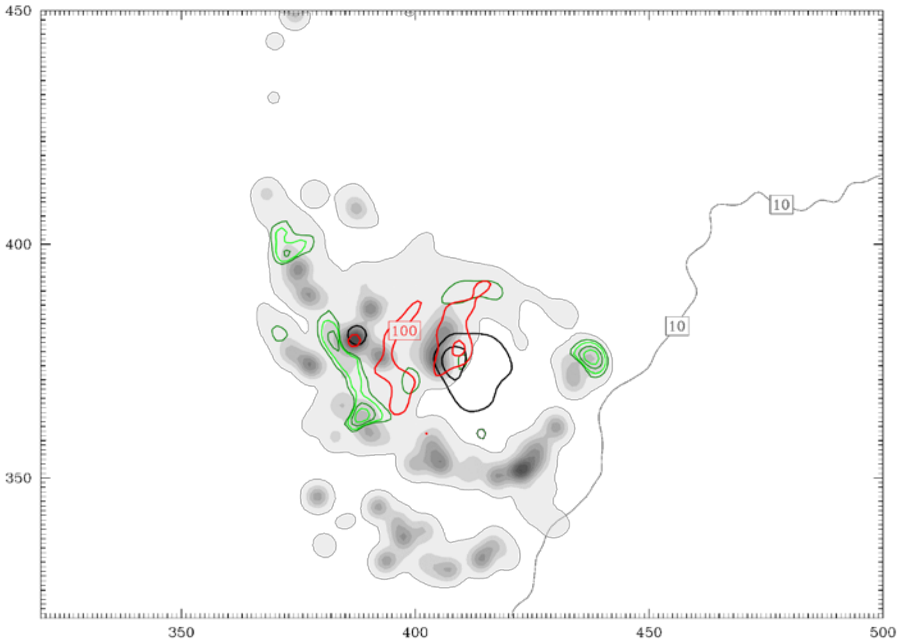


850 mb relative vorticity

500 mb relative vorticity

Diabatic Cooling (Color Contours)

GDAEc　　06Z Sep 16, 700 mb　　GDAEd

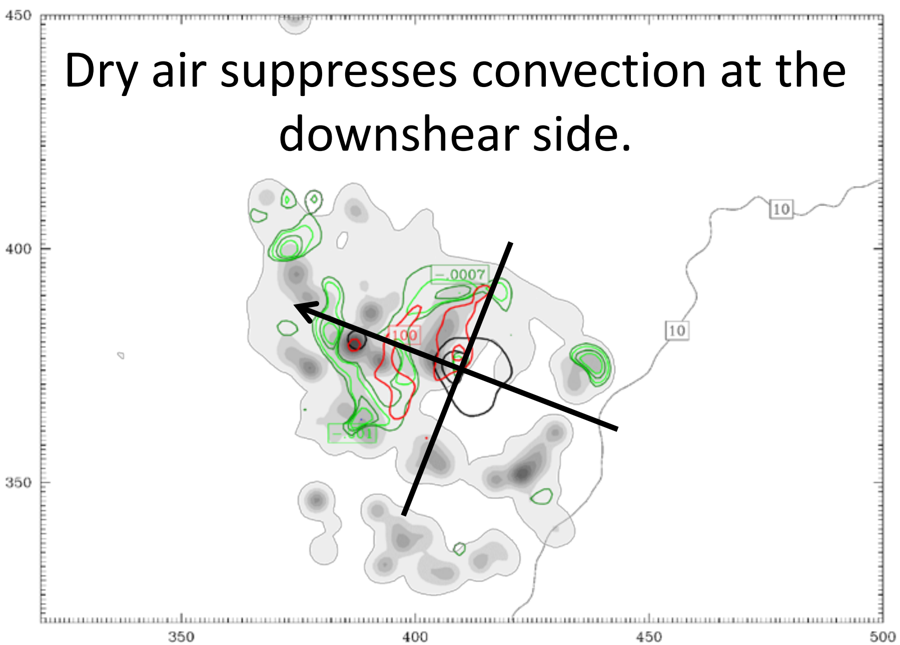


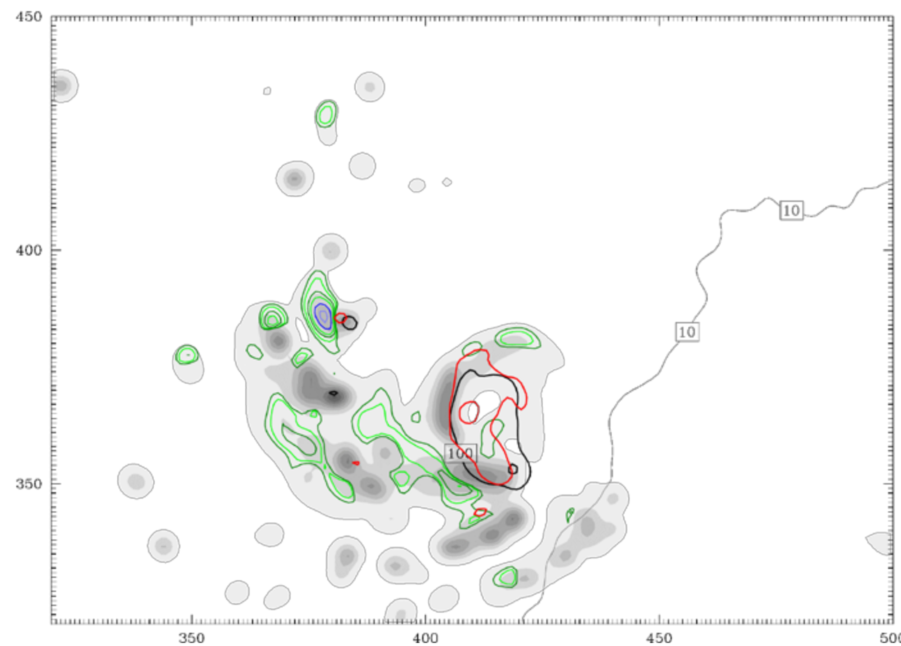
850 mb relative vorticity

500 mb relative vorticity

Diabatic Cooling (Color Contours)

GDAEc 06Z Sep 16, 600 mb GDAEd

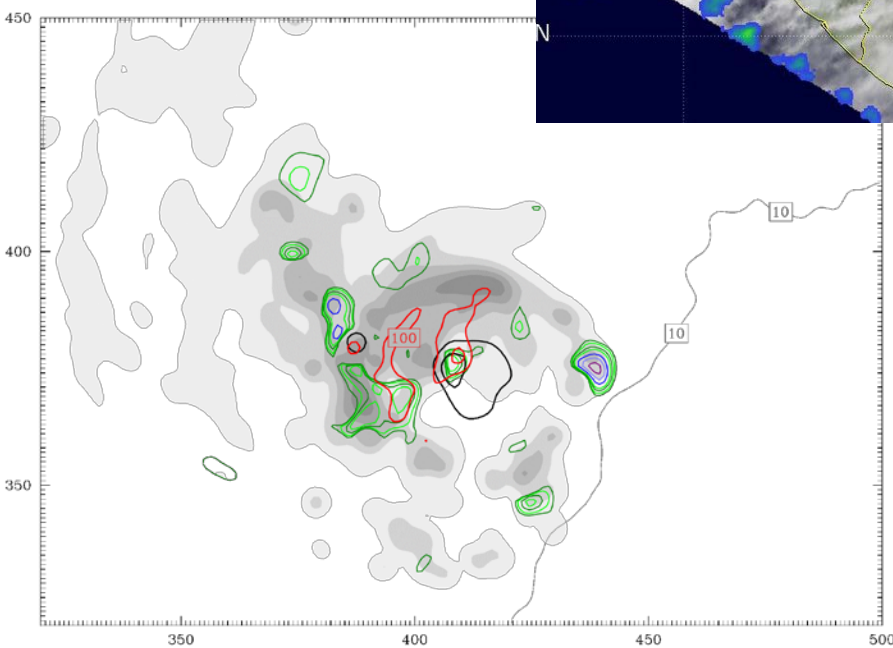


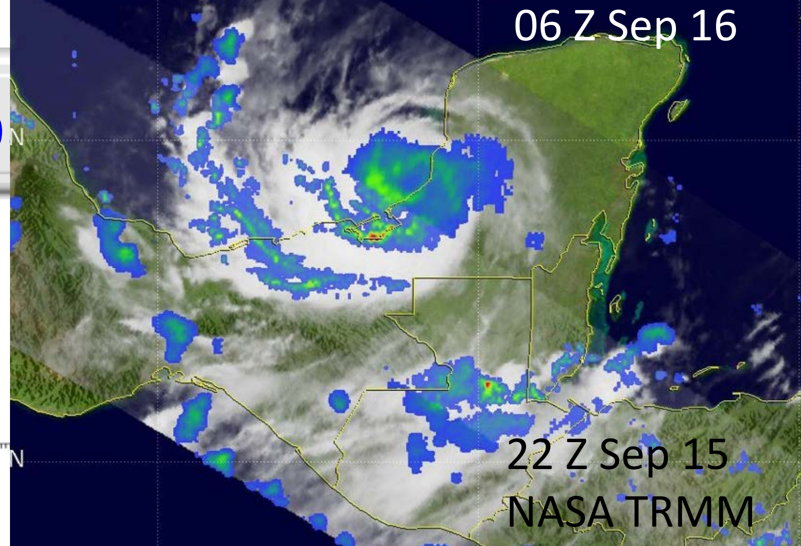


Observations show that the presence of more convective bursts on the downshear side of the storms within R_{MW} is one of the distinct indicators of an intensifying cyclone. (Roger et al. 2013)

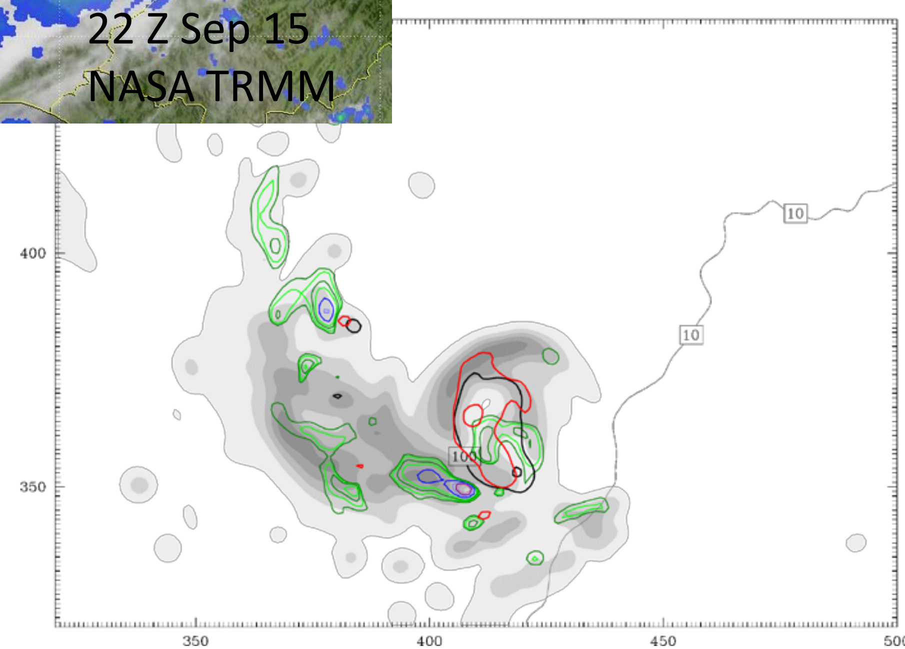
Diab tours)

GDAEc





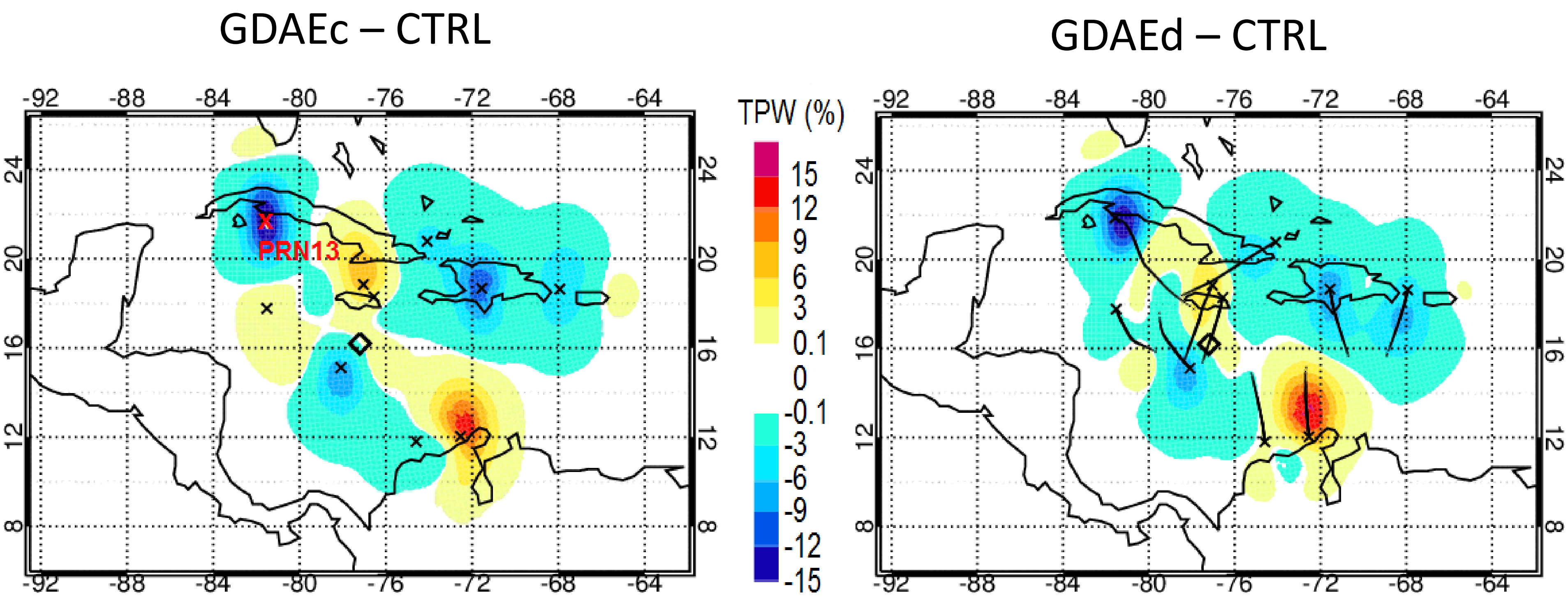
GDAEd



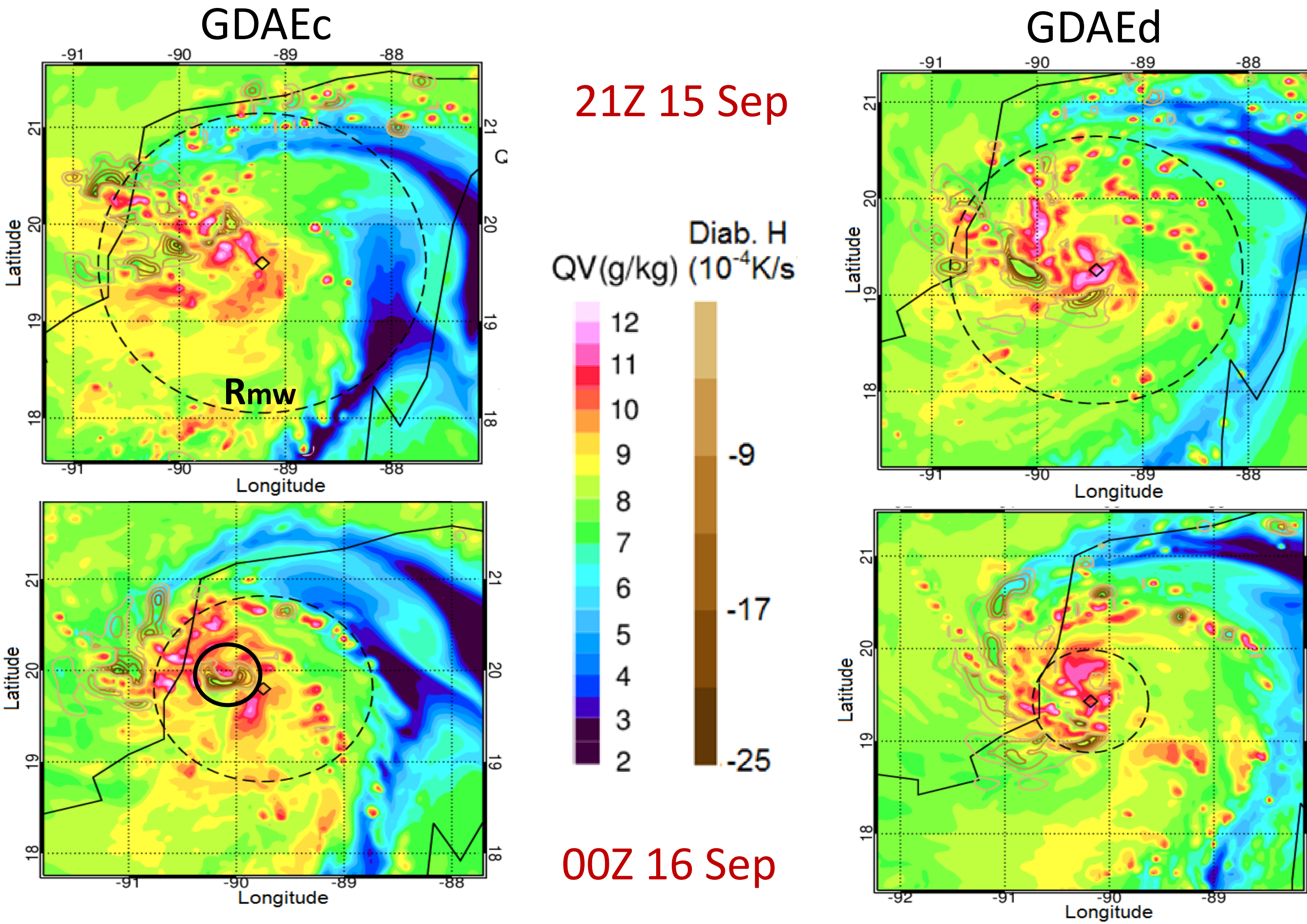
850 mb relative vorticity

500 mb relative vorticity

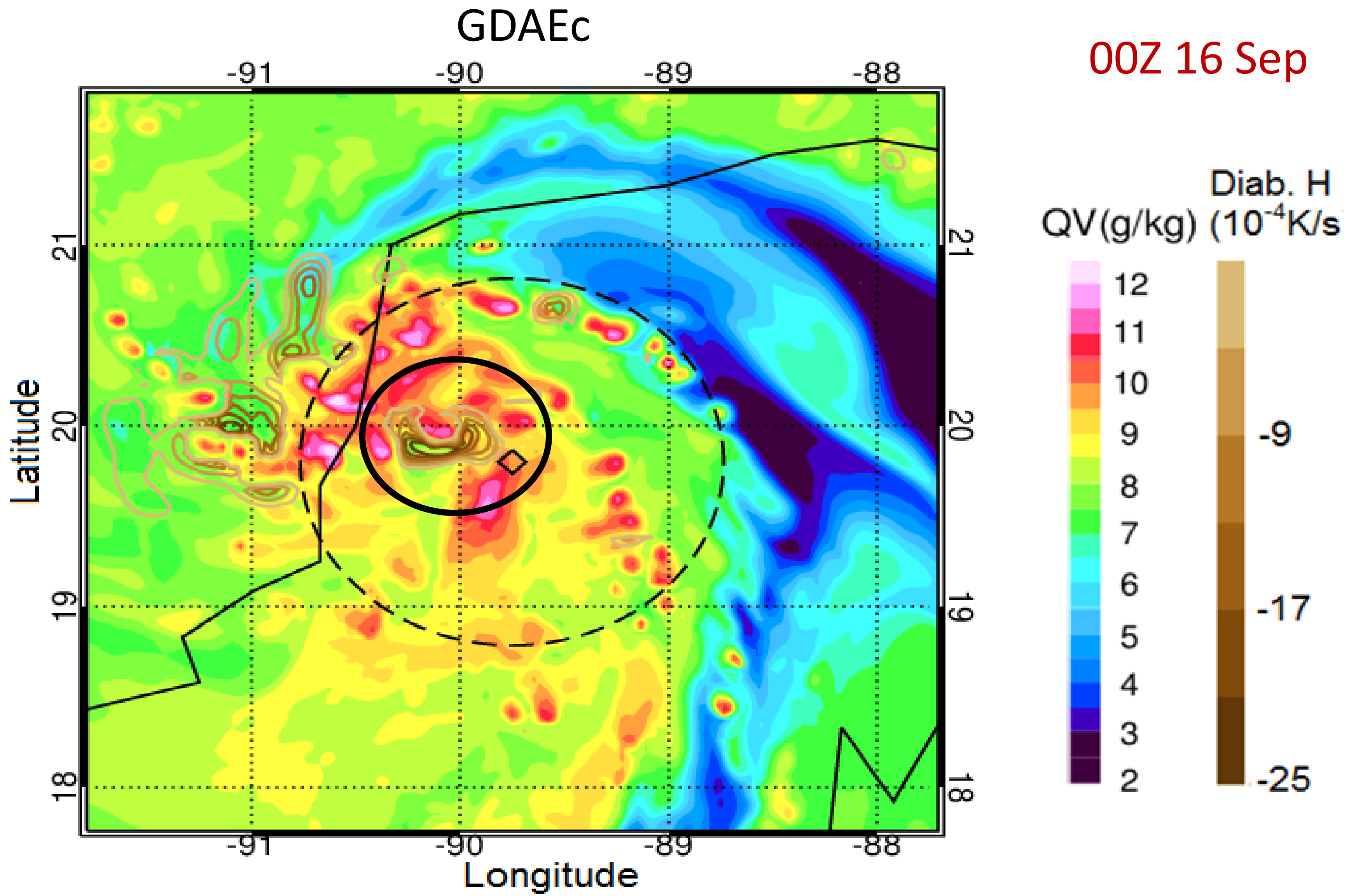
Drier Air and prn 13



Diabatic Cooling @ 650 mb (Color Contours)

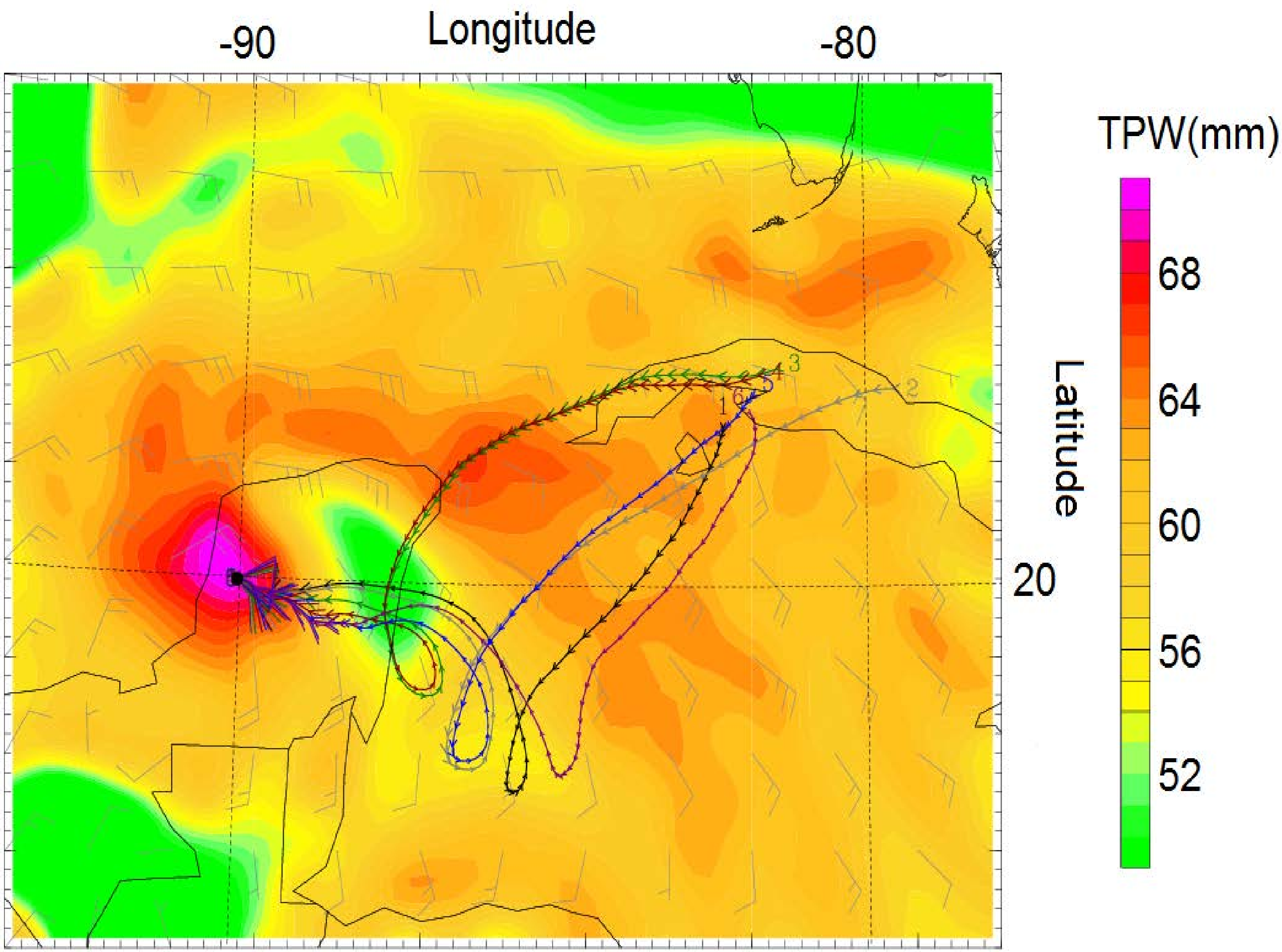


Diabatic Cooling @ 650 mb (Color Contours)

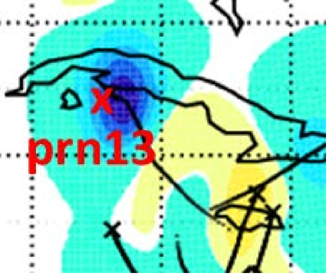


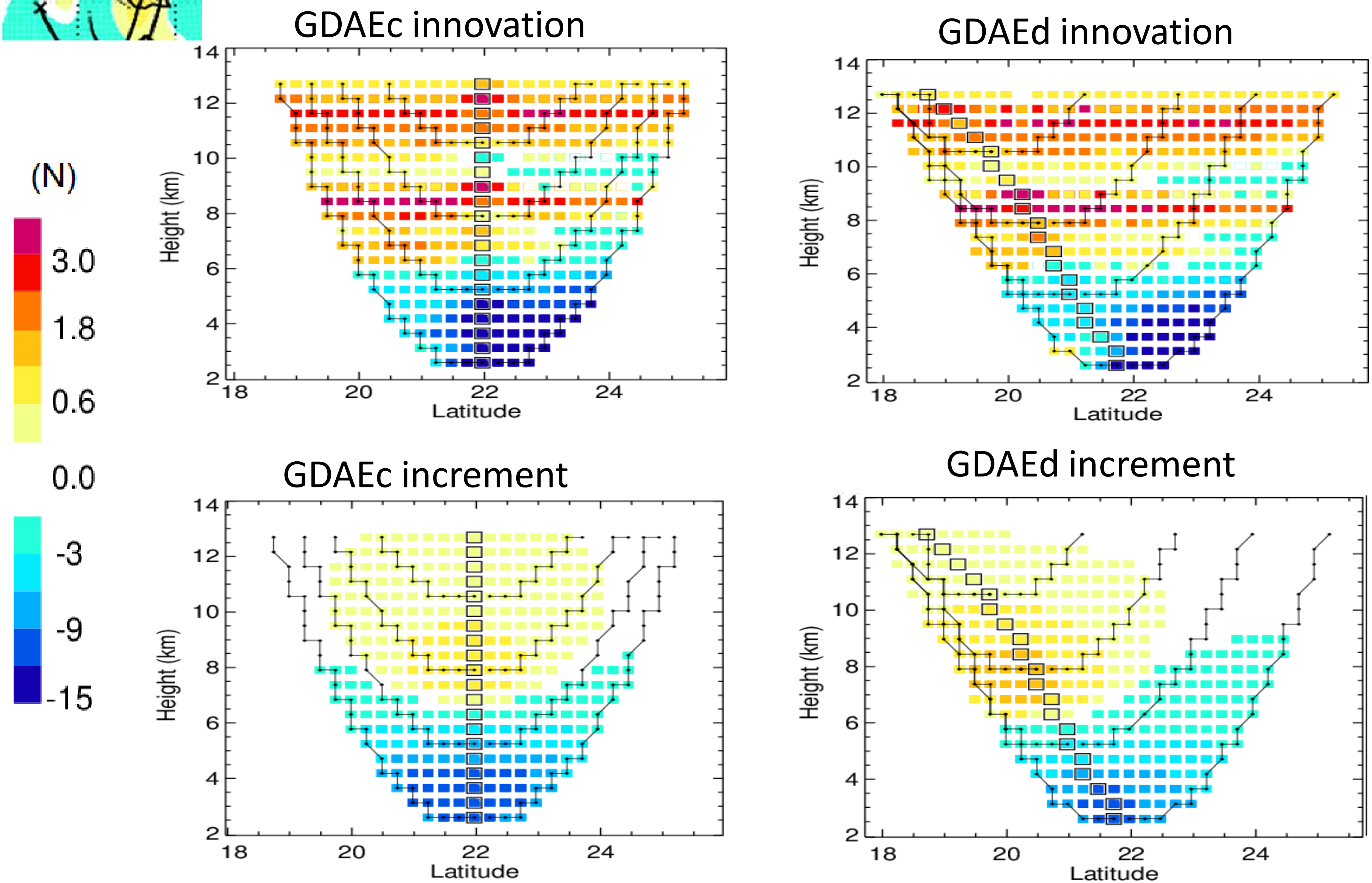
Backward Trajectory (GDAEc)

00Z 16 to 12Z 13 Sep



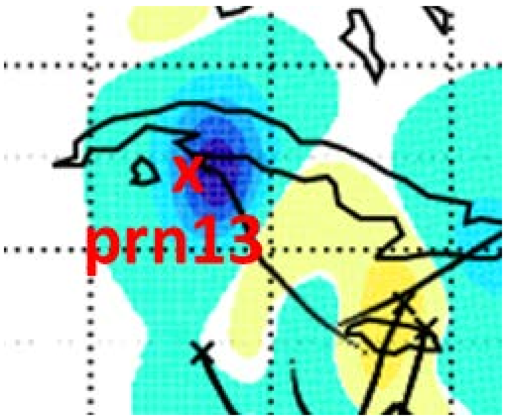
Innovations & Increments (prn 13)

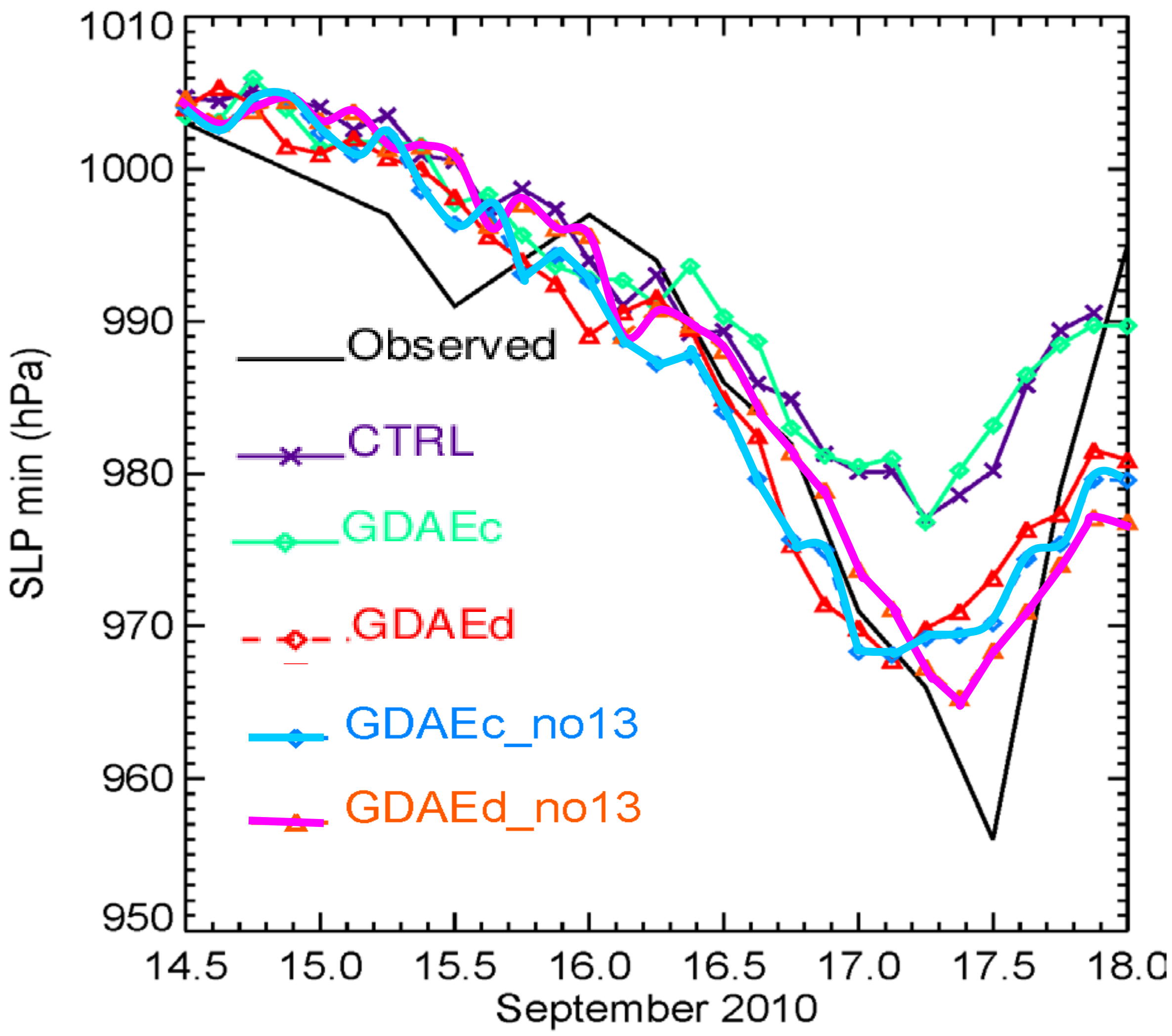




Sensitivity Experiments – Remove prn 13

Min SLP, 12Z 14 Sep – 00Z 18 Sep 2010





Summary

- **ARO data has potential to improve severe weather forecasts.**
- **Assimilating AROs with drifting tangent points gave better results than without drifting. (Drier air intruded into the middle levels of the downshear side of the storm.)**
- **Although in this case study the non-local RO data did not give a better result than the local RO data, the non-local operator should be still preferred.**
- **How can EnKF methods better take the advantage of the information given by non-local observations, which have smaller errors?**

Ongoing Work

- **Repeat the case study using a LETKF system.**
- **Conduct an OSSE study: Colorado Floods in Sep 2013**