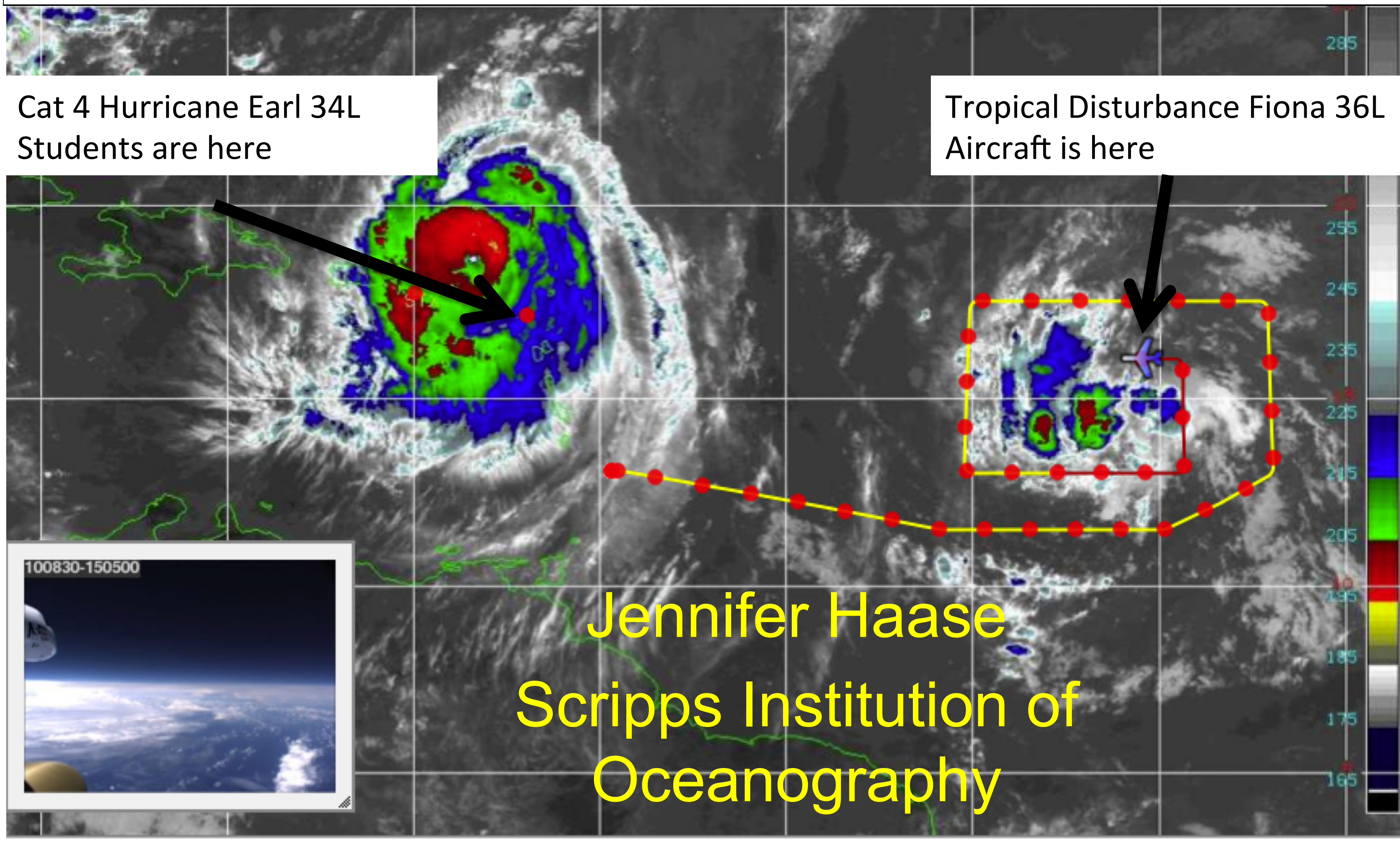
Profiling the moisture environment of developing tropical storms using airborne radio occultation



Jennifer Haase
Scripps Institution of Oceanography

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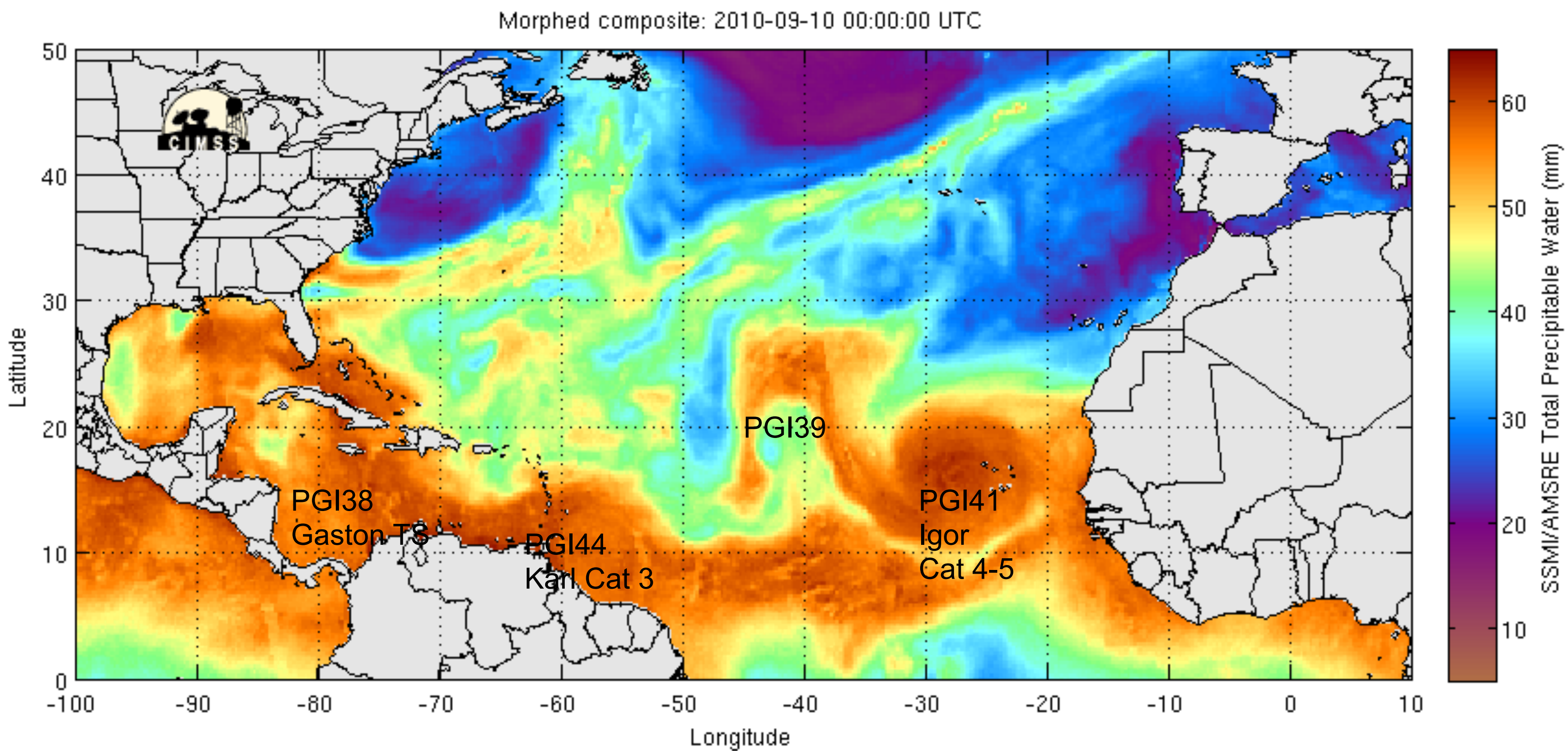
Overview

- Objectives of the PRE-Depression Investigation of Cloud systems in the Tropics campaign (PREDICT)
- Description of the airborne GPS remote sensing concept
- Temporal and spatial refractivity variations in pre-hurricane Karl
- Recent improvements in techniques
- Other GNSS observation capabilities

Focus on tropical waves

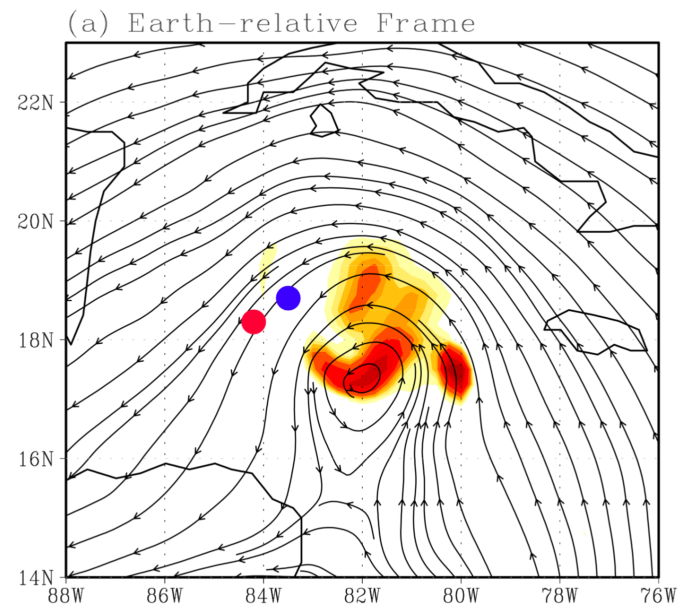
CIMSS MIMIC TPW product



While more than 80% of intense hurricanes in the Atlantic originate as African easterly waves (Landsea, 1993) most easterly waves do not develop into hurricanes. Which waves will develop?

Hypothesis

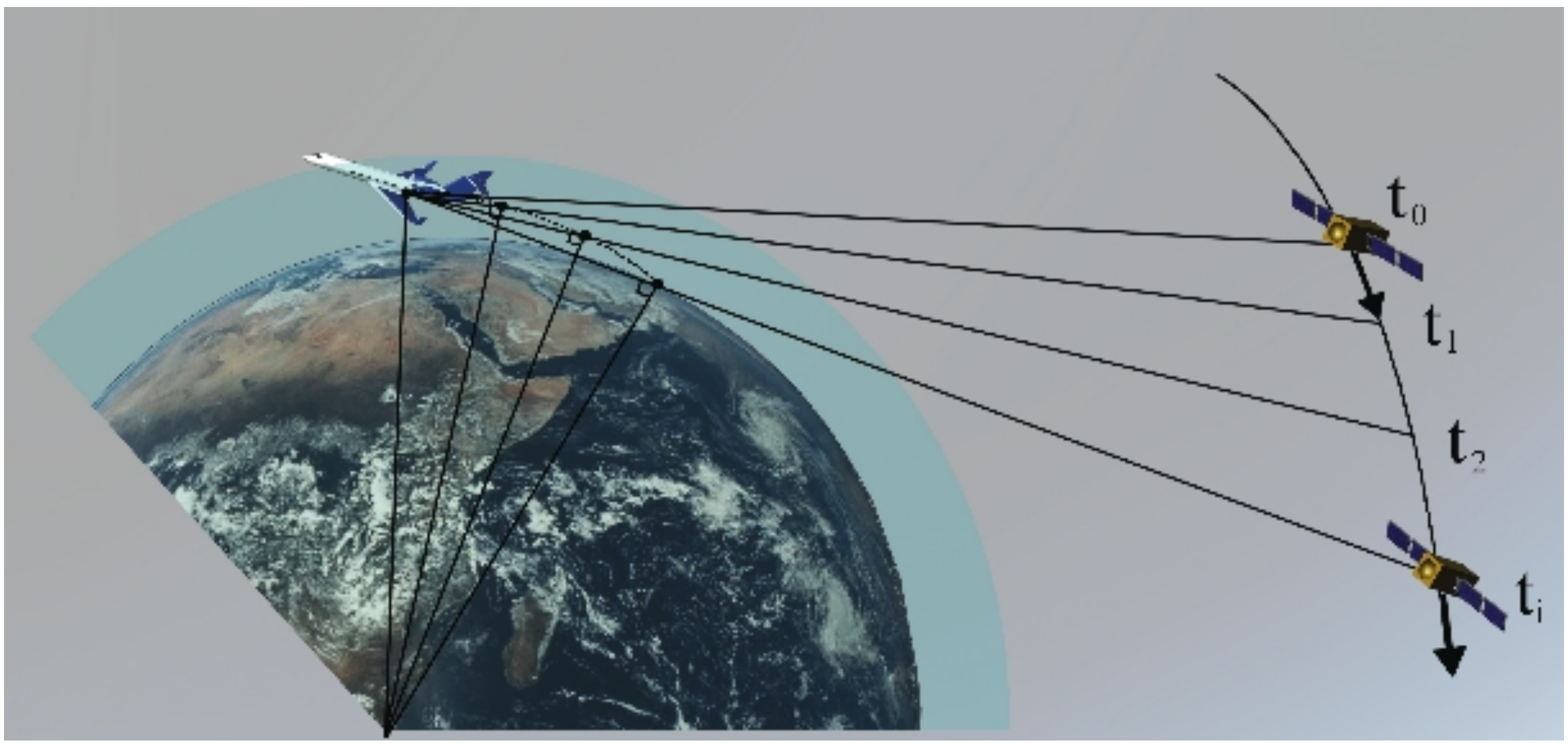
- When isolated from the surroundings, mid-to-lower tropospheric moisture (surface to ~6 km) is enhanced due to the influence of deep convection as air recirculates within the region.
- Tropical depression formation is greatly favored in the recirculation region where the wavespeed in the trough axis is the same as the mean flow.
- Our mission: use the unique capabilities of GPS remote sensing to track the evolution of the background atmospheric properties in which the mesoscale dynamic features are embedded.



- Describe to what extent we can detect whether moisture is increasing over time leading up to the formation of a tropical depression.

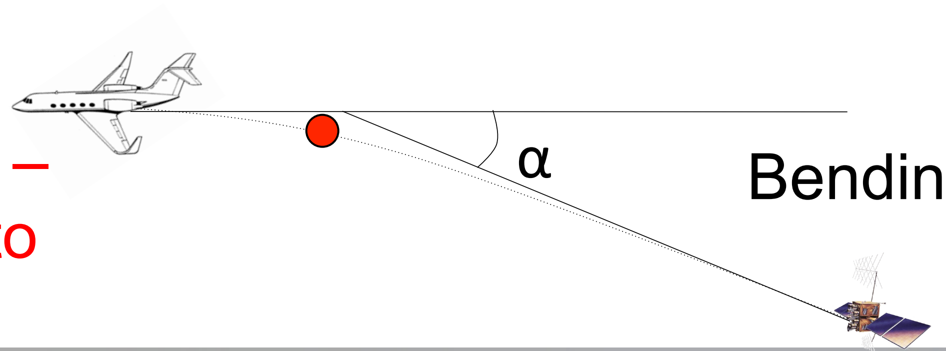
Airborne GPS radio occultation

- •Side-looking GPS receiver tracks setting and rising satellites
- •Nearly horizontal raypaths experience refractive delay
- •Atmospheric humidity profile is derived from refractive delay

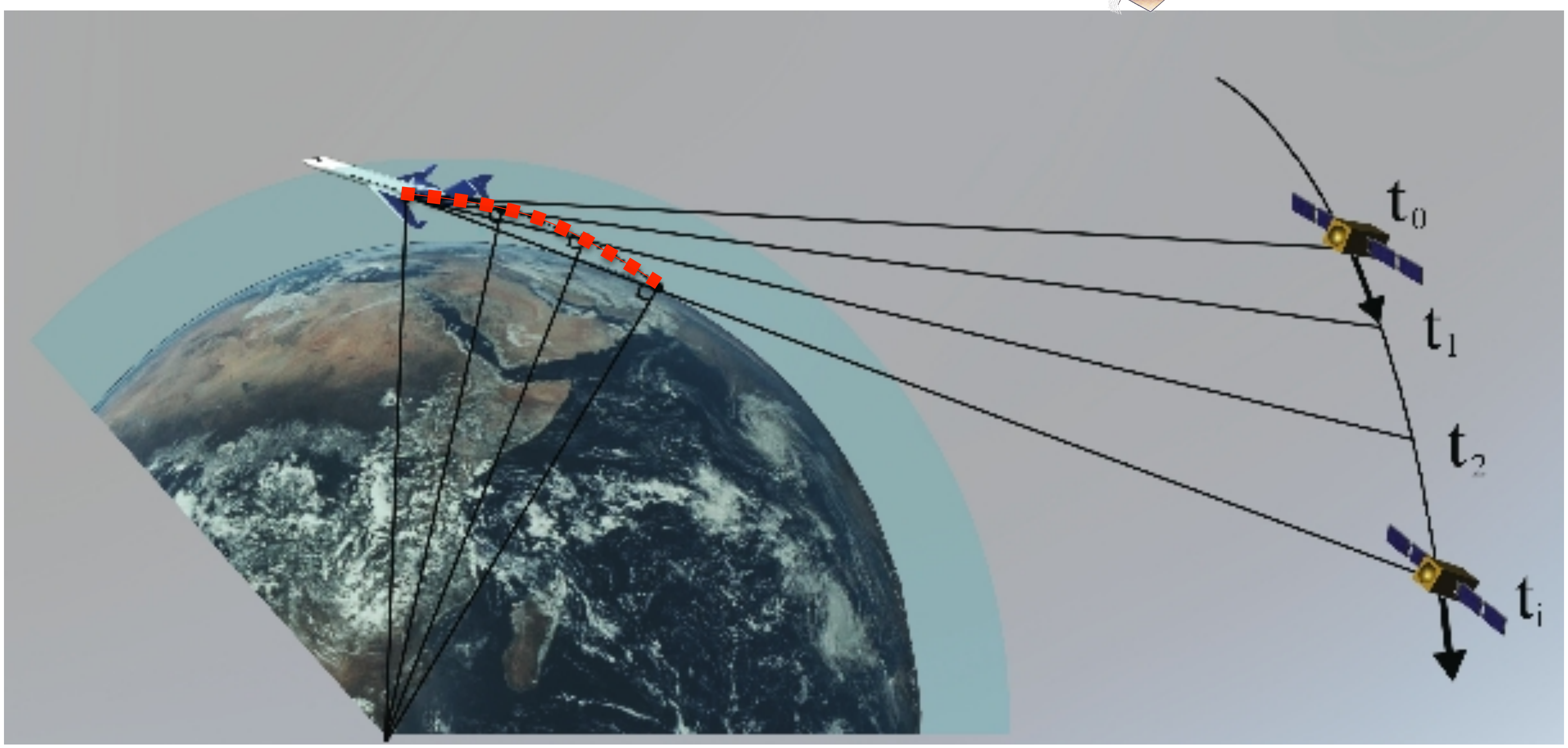


Refractive bending angle

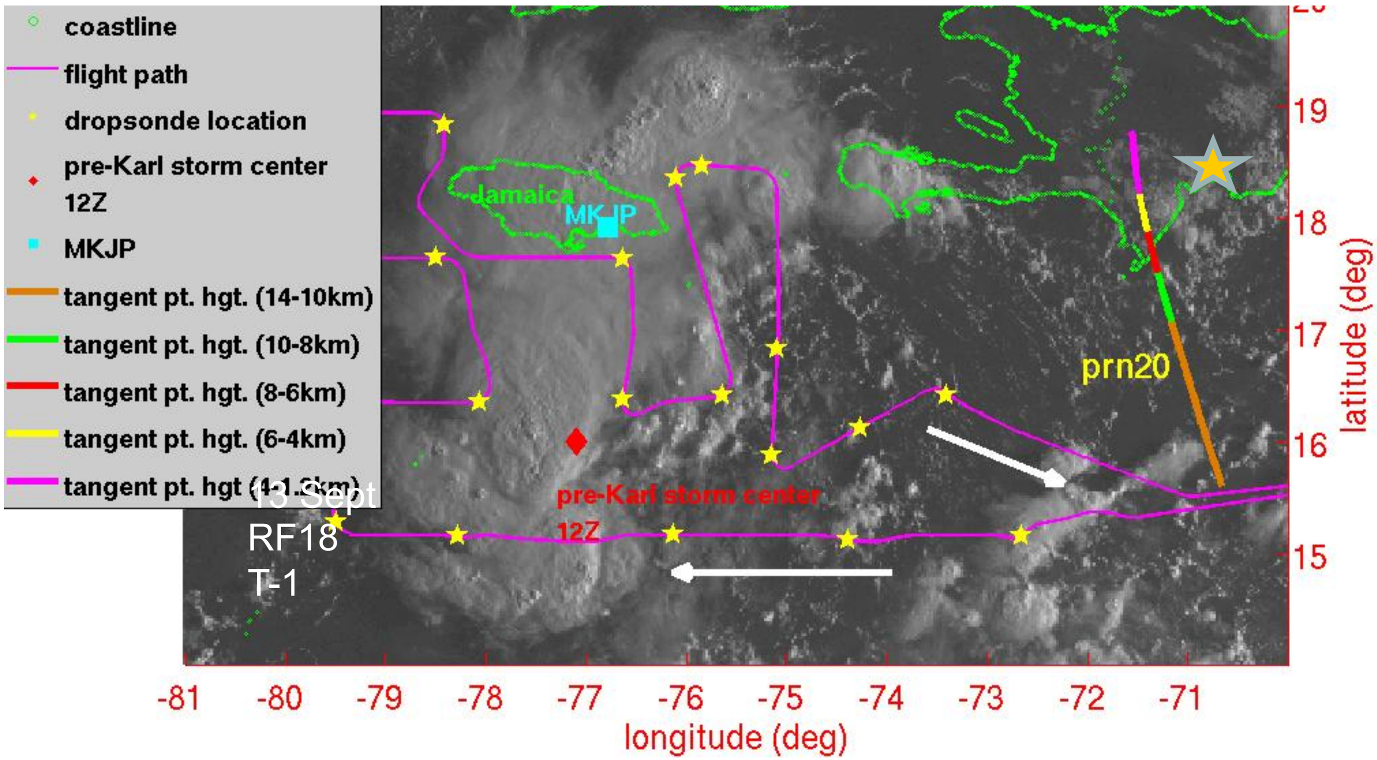
Tangent point – point closest to Earth surface



Bending angle

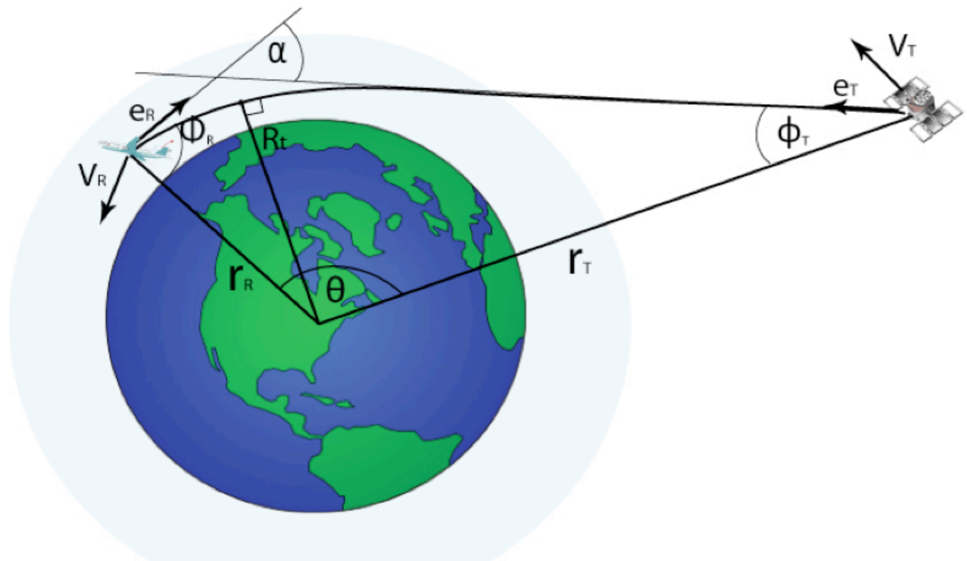


Observation geometry for pre-depression convective systems



- Dropsondes are point measurements (yellow stars)
- ARO is a slanted profile
- Representative "occultation point" used for comparison is tangent point at 500 hPa
- Tangent point drift in the horizontal varies ~ 200 – 600 km

GPS radio occultation theory



- GPS signals are refracted in the atmosphere
- Measure the difference between the observed distance and the straight line
- Refraction causes a Doppler shift in the carrier frequency
- The bending angle is an integral of the refractive index, which depends on *P,T, and e*

$$N = (n-1)\cdot 10^6 = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

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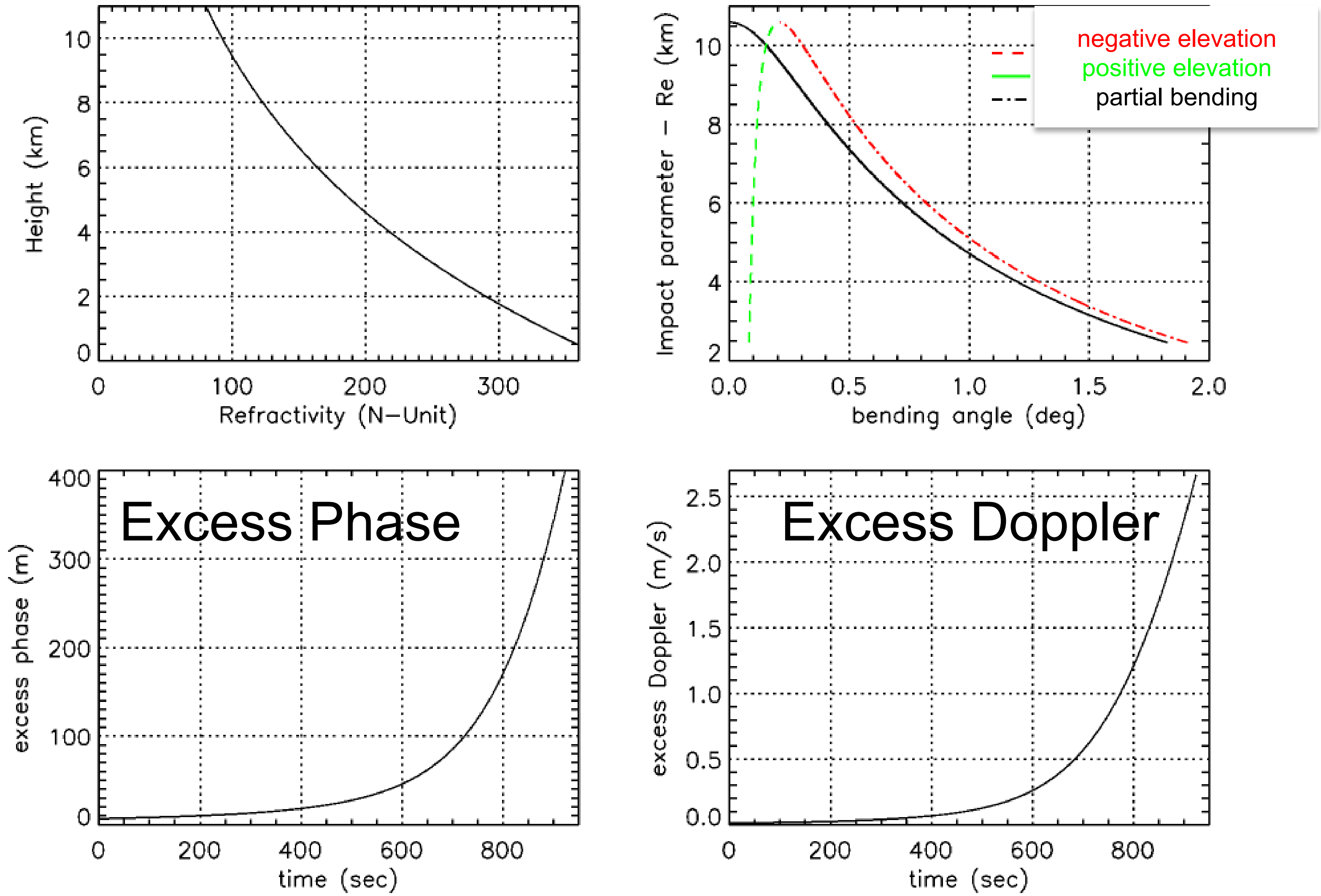
Refractivity

Bending angle

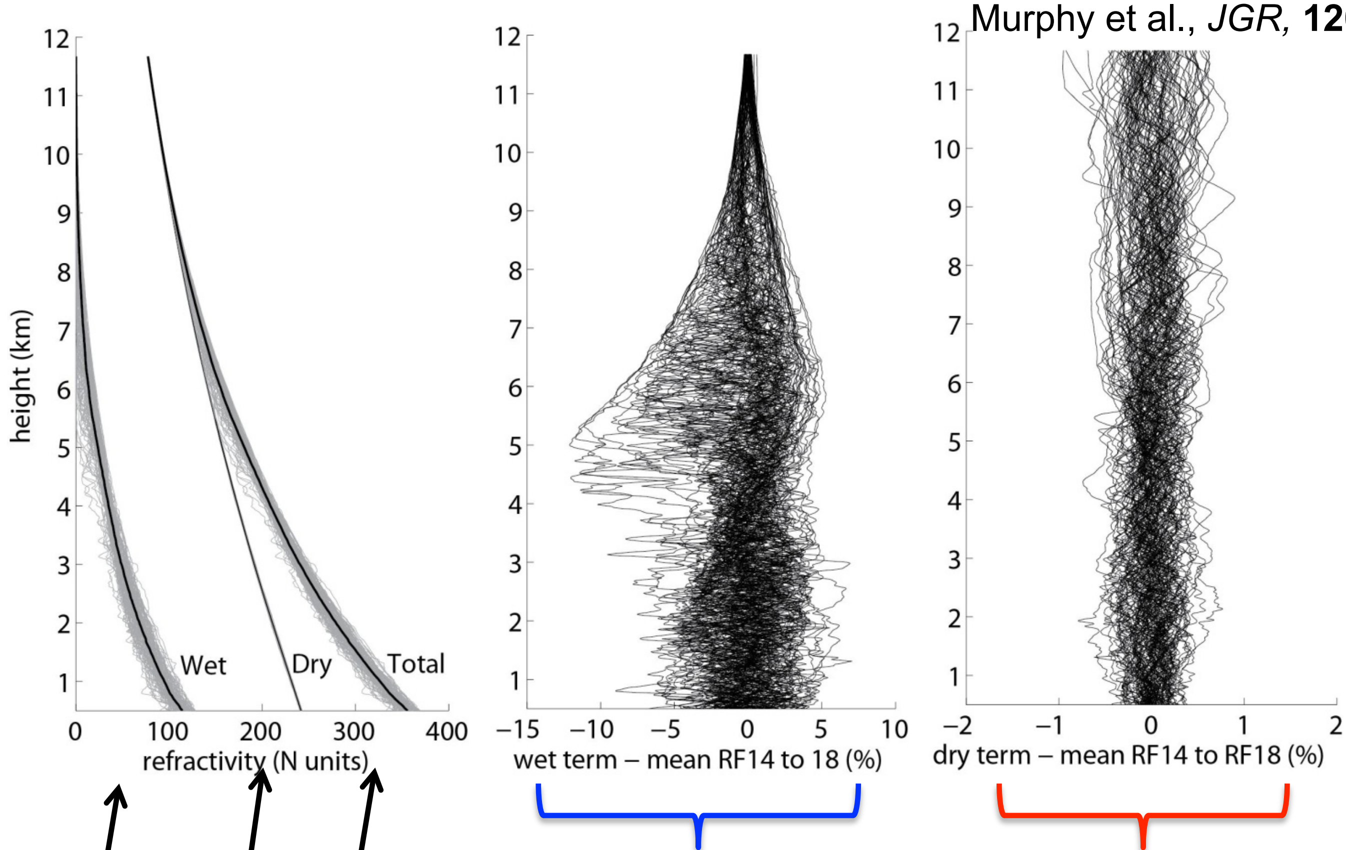


Challenging measurements: maximum doppler 2.5 m/s

velocity noise 0.005 m/s

Reference background environment from dropsondes

Murphy et al., *JGR,* **120,** 5, 2015



$$N_{wet} + N_{dry} = N_{total}$$

$$N_{wet} = 70.4\frac{P_w}{T} + 3.739\times10^5\frac{P_w}{T^2}$$

$$N_{dry} = 77.6\frac{P_d}{T}$$

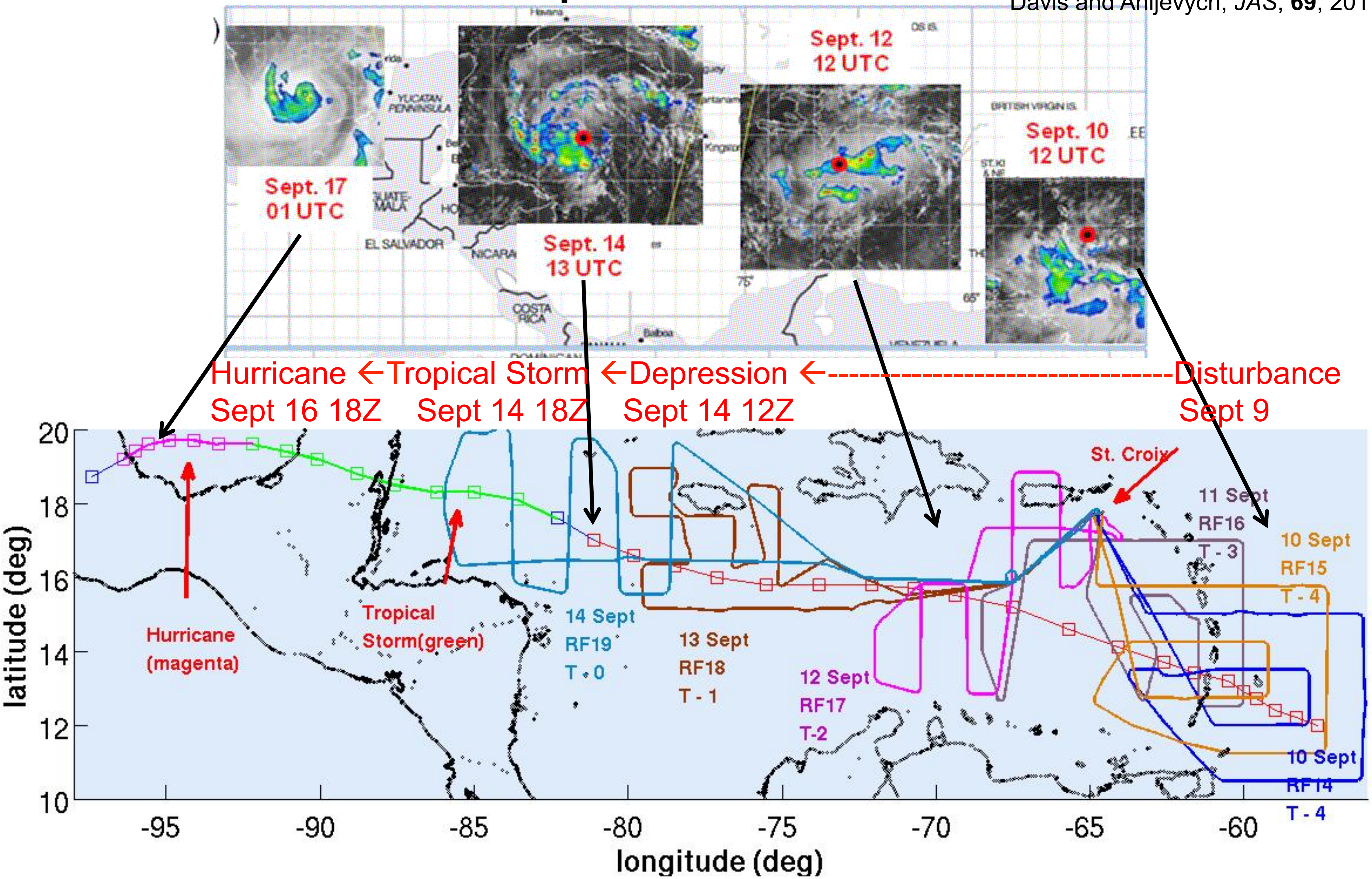
- Refractivity is calculated from dropsonde *P, T, e* to understand variability
- -10% to 5% of refractivity variation is due to moisture
- Refractivity variations are dominated by moisture up to 9 km in the tropics, a fact not previously appreciated

PREDICT Campaign

- Attempt to sample the tropical wave over the transition from disorganized convection of a tropical disturbance, to the organized formation of the low pressure circulation center of a tropical depression.
- A total of 26 missions were flown with the NSF/NCAR GV aircraft
- Sampled 8 tropical disturbances.
- 3 or more missions were conducted in 4 cases: (Fiona, ex-Gaston, Karl and Matthew)
- 2 disturbances developed into hurricanes (Karl & Matthew), 6 did not.

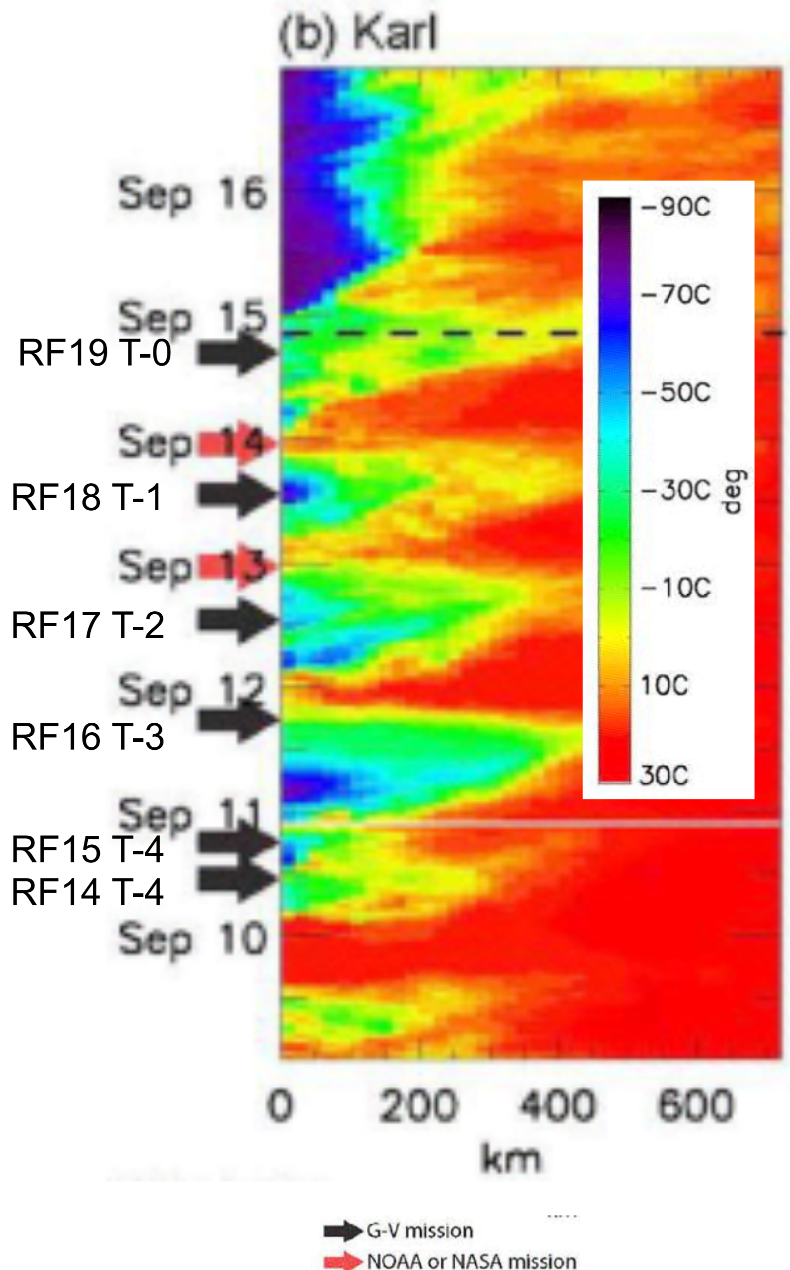
Development of Karl

Davis and Ahijevych, *JAS*, **69**, 2011



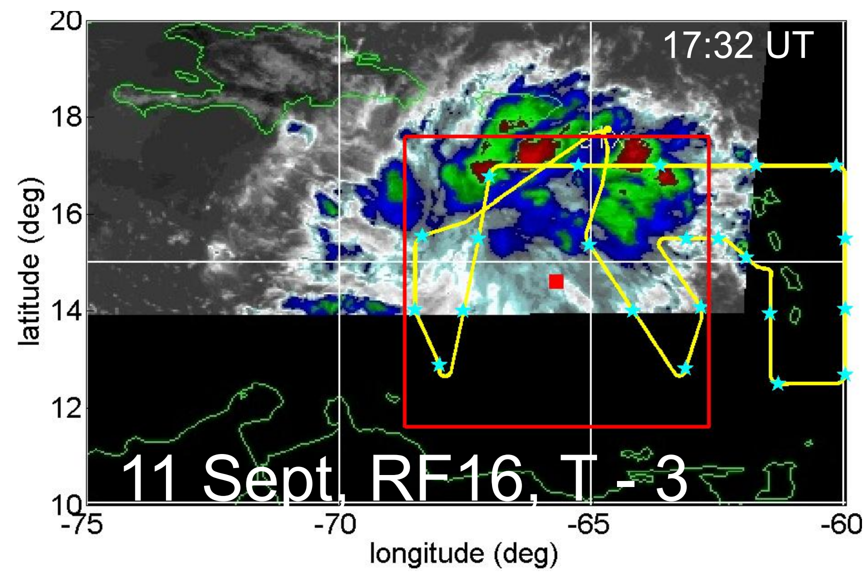
- Six PREDICT research missions, RF14 – 19 flown to sample pre-Karl system, releasing 14-16 dropsondes each

Pre – Karl diurnal convective cycle from IR



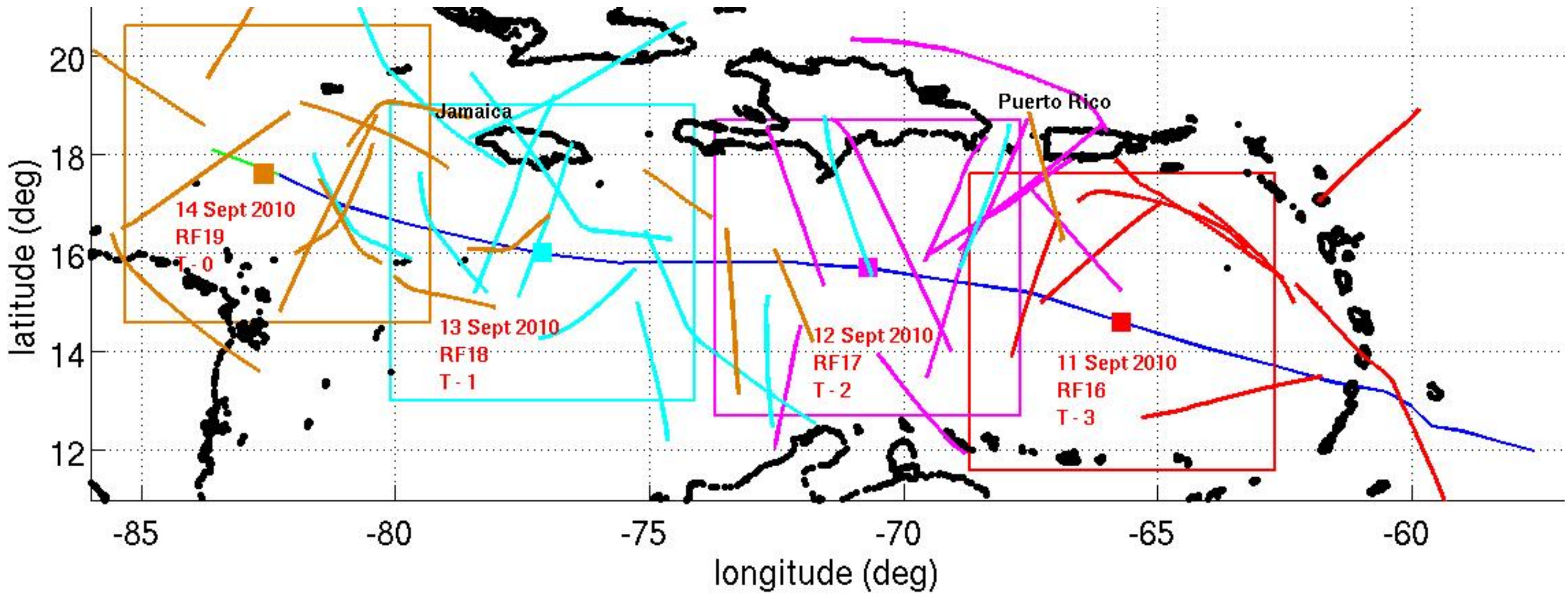
The pre-Karl system exhibited a diurnal convective pattern in IR cloud top temperature until genesis on 14 September

Pulse of deep convection on 11 September



Davis and Ahijevych, *JAS*, **69**,2011

Many profiles to look at evolution of mean

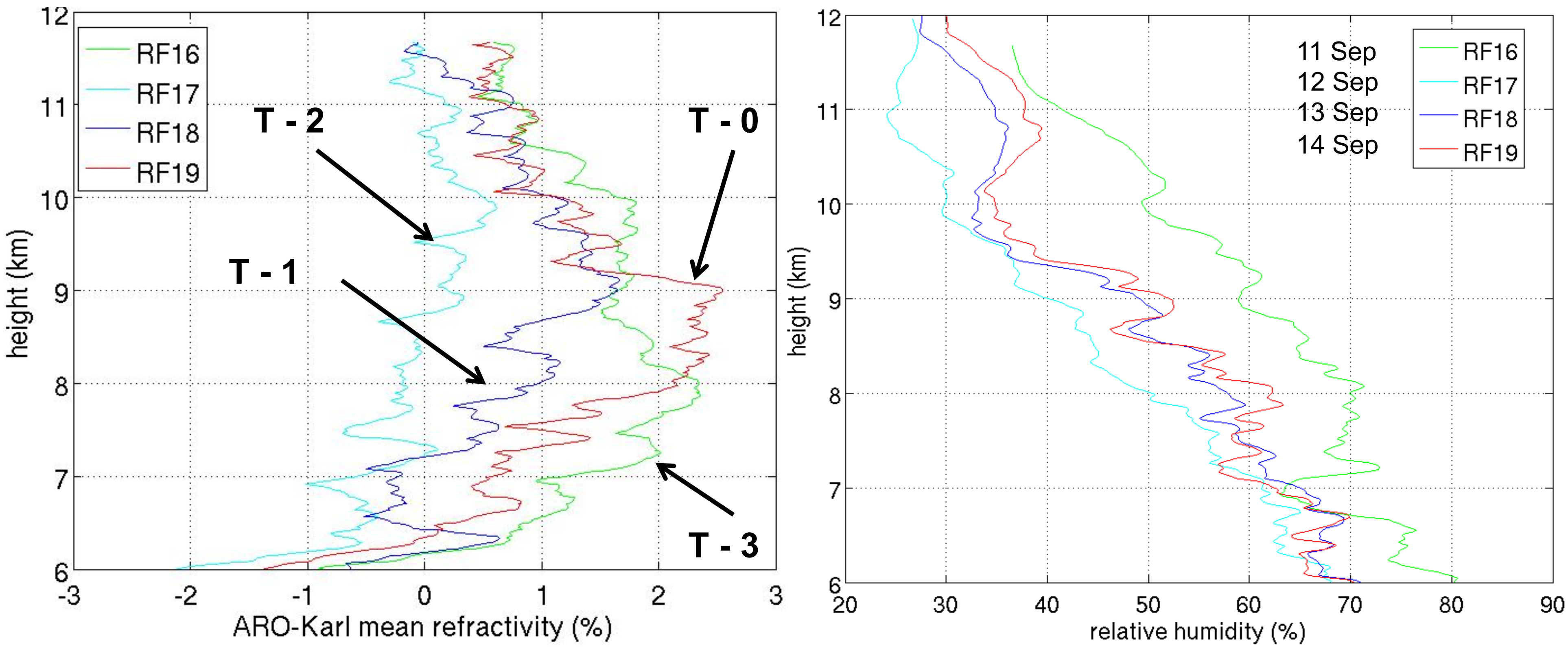


- To investigate temporal moisture evolution, a 6 x 6 meso-α box (Wang, 2012) was defined surrounding the storm location for each day 11-14 Sept, T-3 to T-0

- ARO open loop profiles were averaged within the region for each flight.

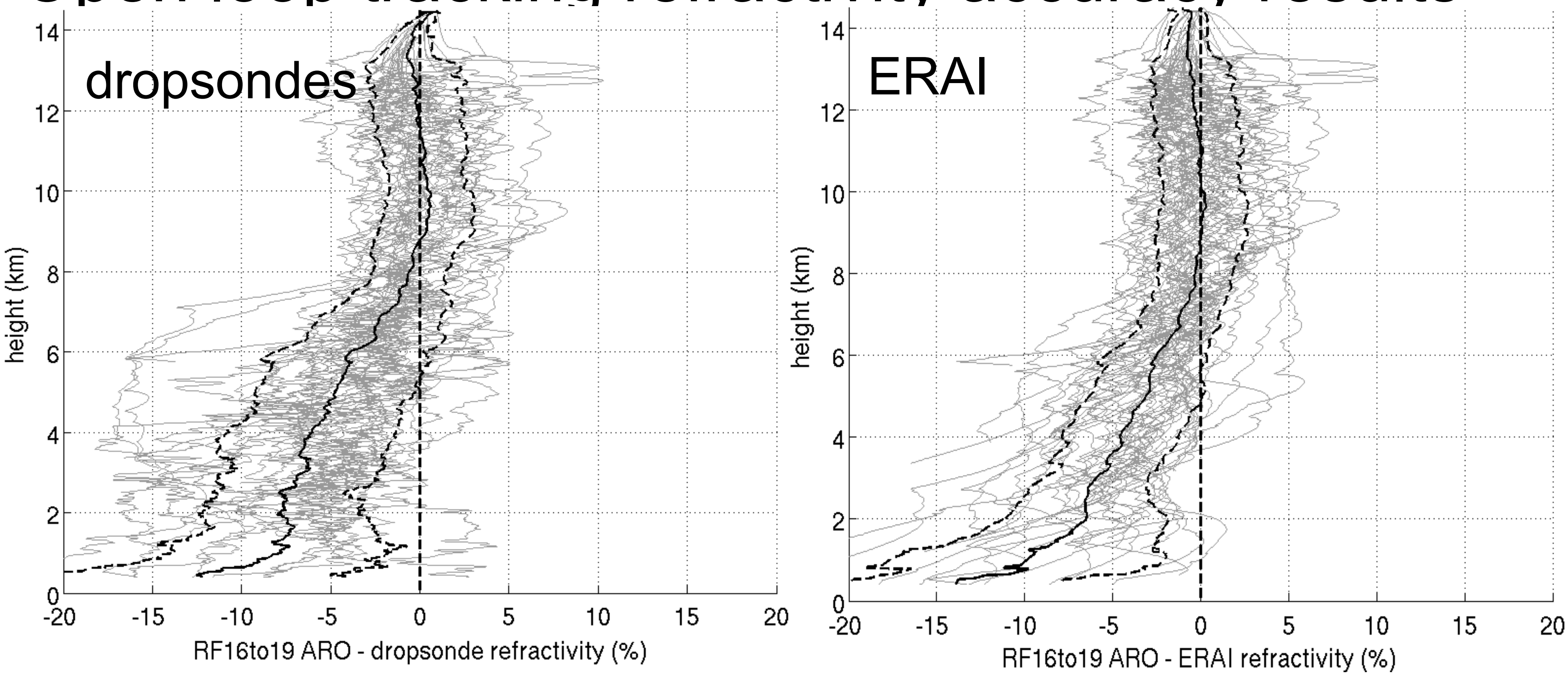
Wang, Z., *J Atmos Sci,* **69**, 2012

Moisture variability of ARO during development



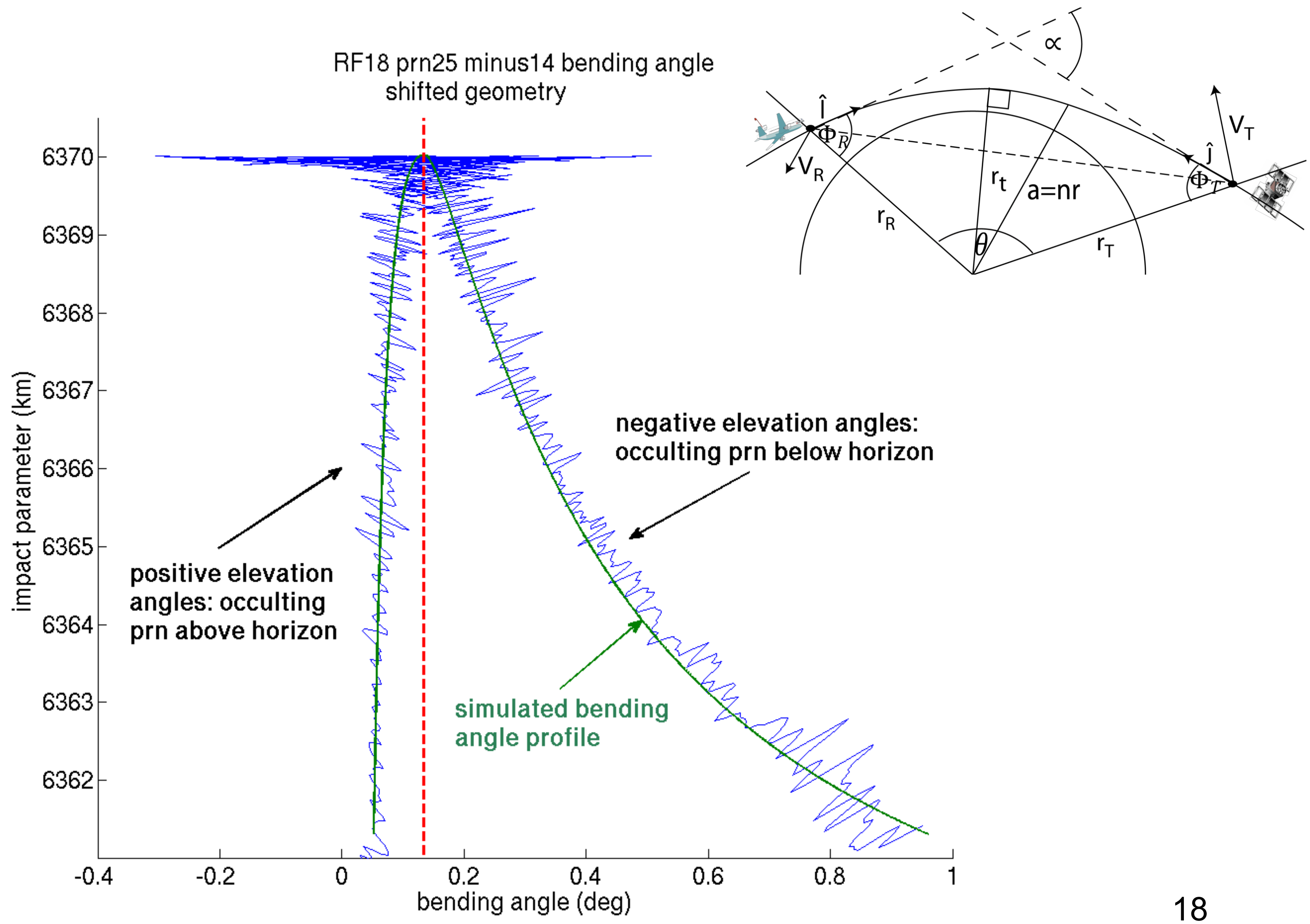
- ARO was consistent with general moistening over T-2 to T-0 similar to dropsonde observations in the same region.
- Both refractivity and moisture on 11 Sept, T-3 were high compared to the other flights.
- This was the day of the pulse of convection seen in the IR in Davis and Ahijevych 2011

Open loop tracking refractivity accuracy results

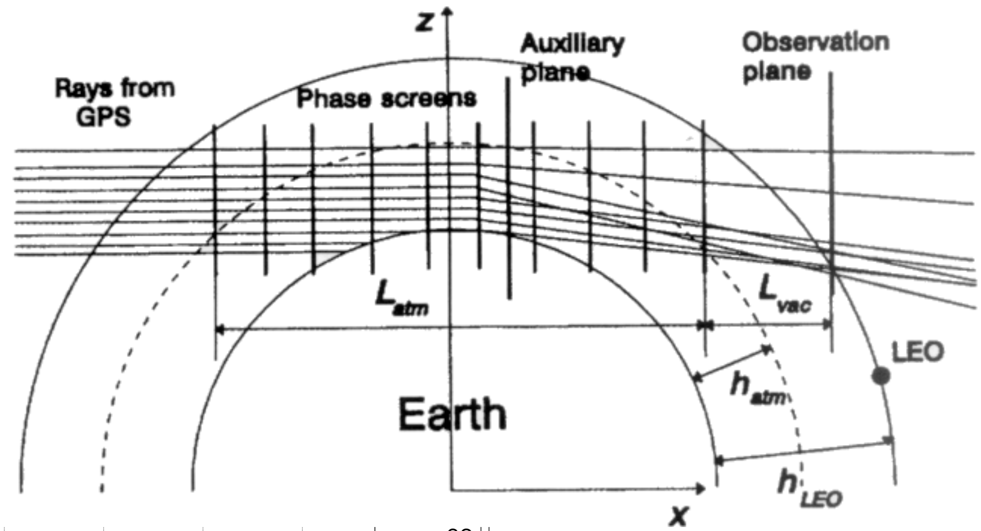


- Standard deviation of ARO - dropsondes ~ 2-3 % above 6km.
- Increasing negative bias below 8 km where multipath is likely
- Similar statistics for comparison with European Center for Medium scale Weather Forecasting Interim Reanalysis (ERAI)

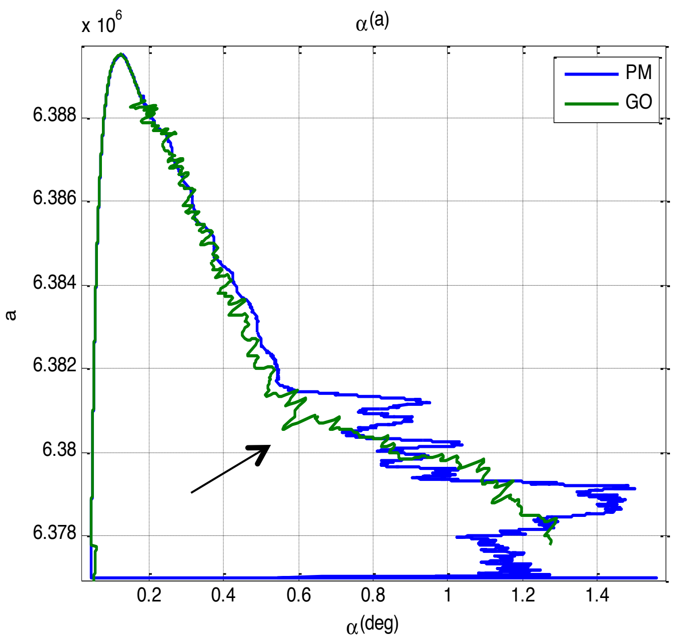
Bending angle calculated using geometric optics

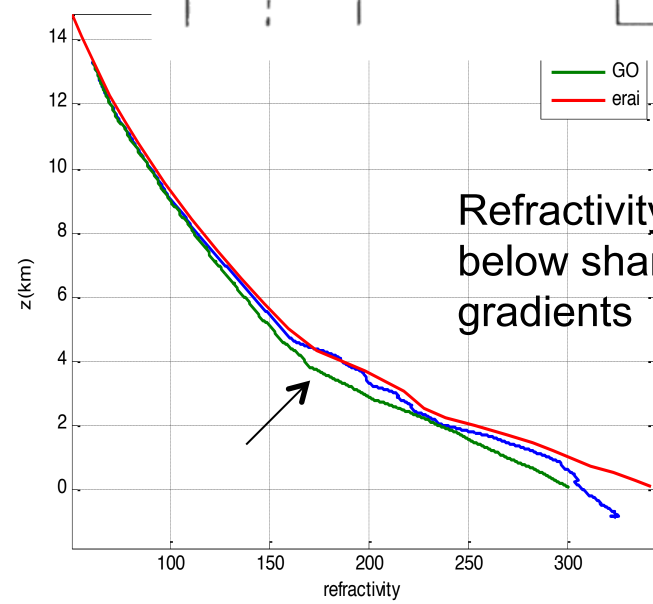


Atmospheric multipath



Bending angle is underestimated at sharp atmospheric gradients



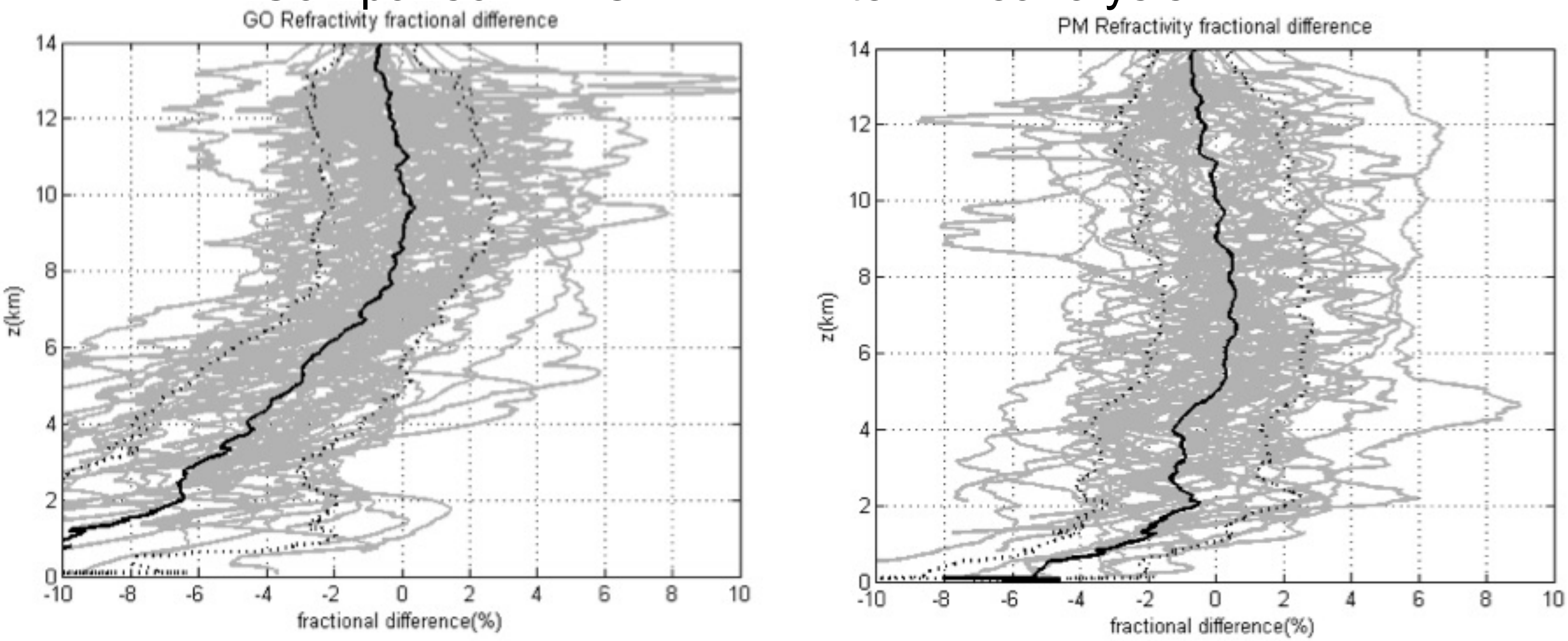


Refractivity is underestimated below sharp atmospheric gradients

- Atmospheric multipath leads to multiple rays contributing to observed amplitude and phase at the observation point

Phase Matching Fourier Spectral Inversion

Comparison ARO – ERA-Interim reanalysis

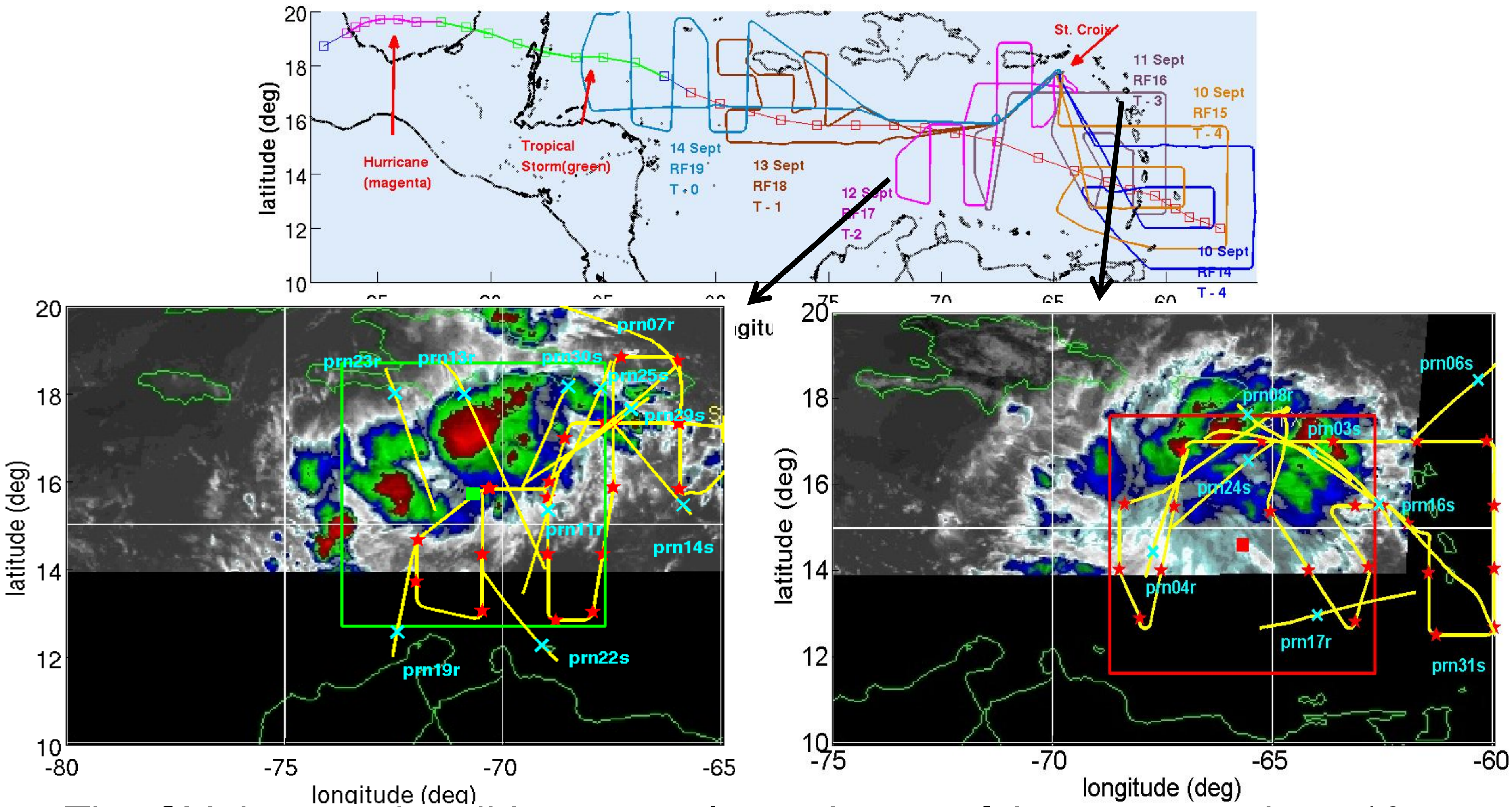


(a) GO

(b) PM

- Phase matching does not assume 1:1 relationship between Doppler shift(t) and bending(a)
- Properly separates information from multiple rays with different Doppler shift
- Reduces bias below 8 km

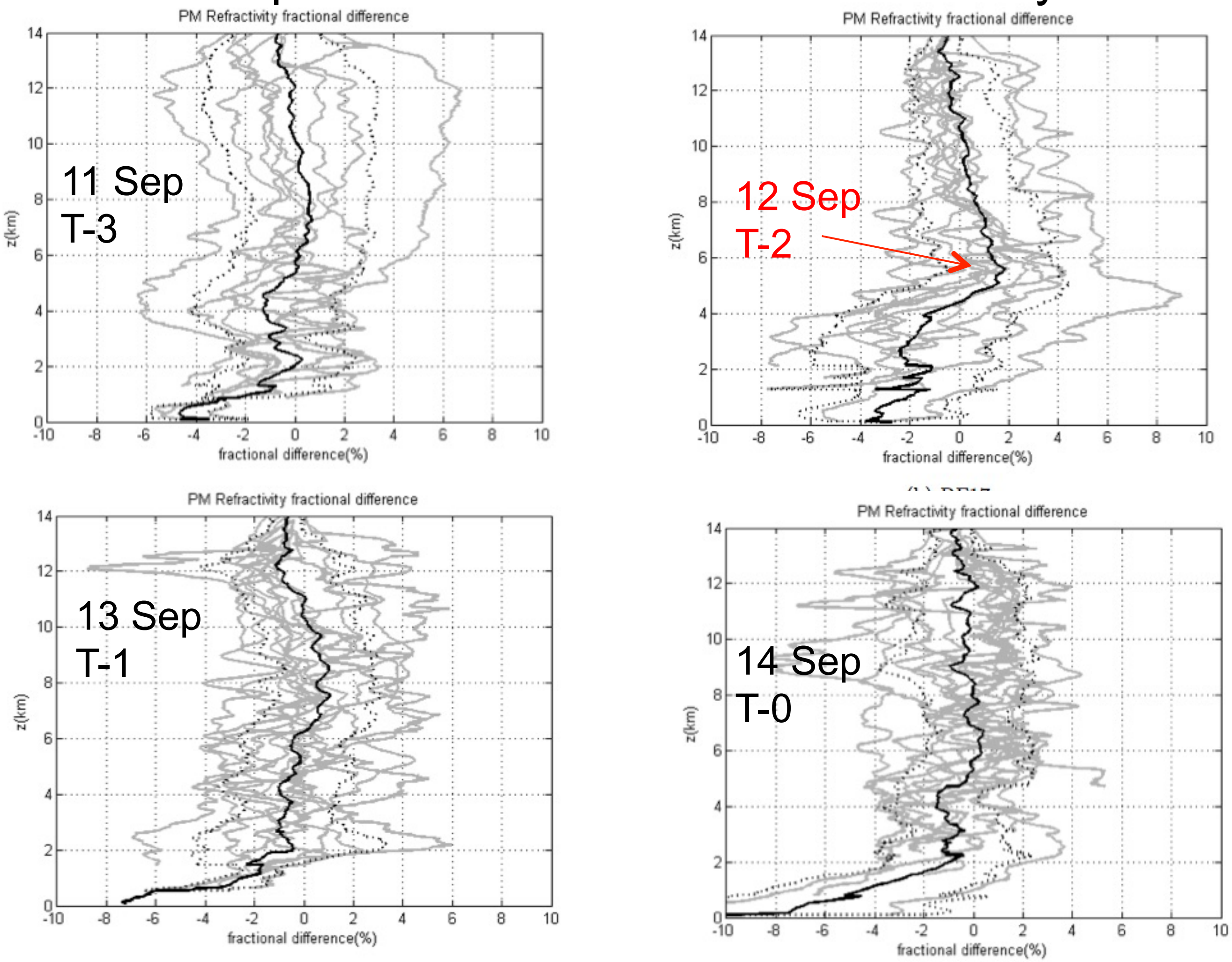
Complementary to dropsondes



- The GV dropsondes did not sample northwest of the storm track on 12 September because of flight safety restrictions over deep convection.
- Side-looking ARO samples this deep convection, complementary to dropsondes, through clouds and heavy precipitation.

ARO samples moist storm center on day T-2

Comparison ARO – ERA-Interim reanalysis

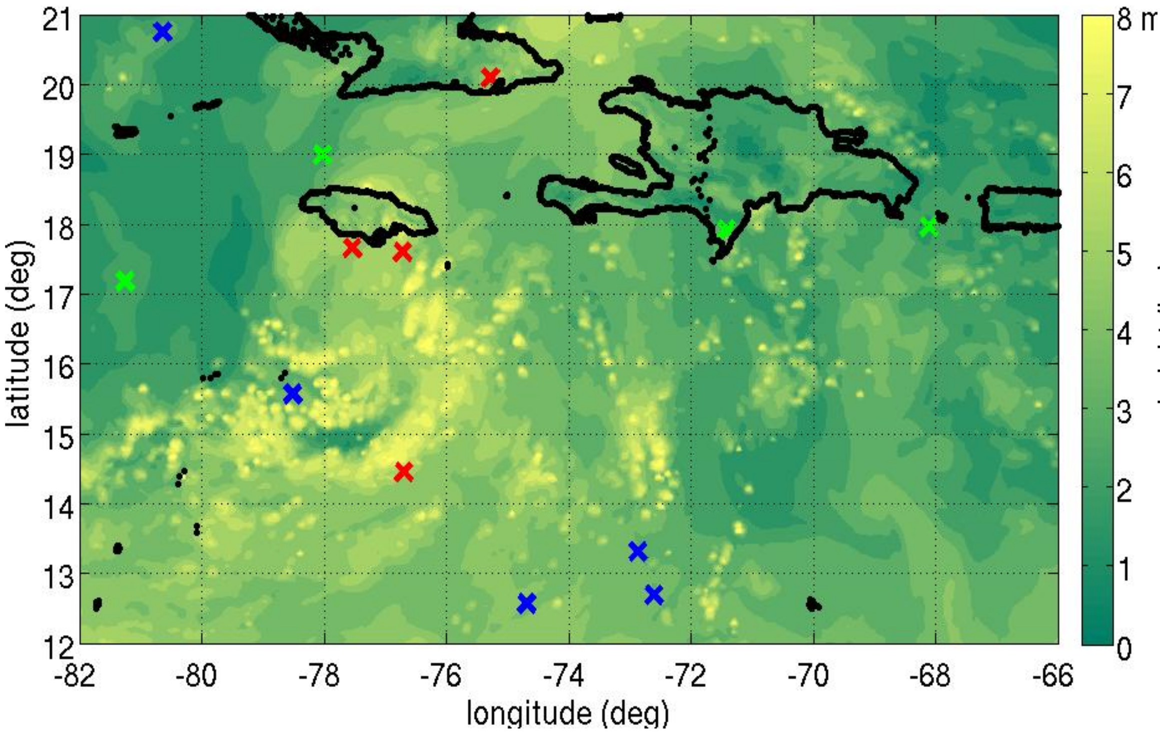


(c) RF18

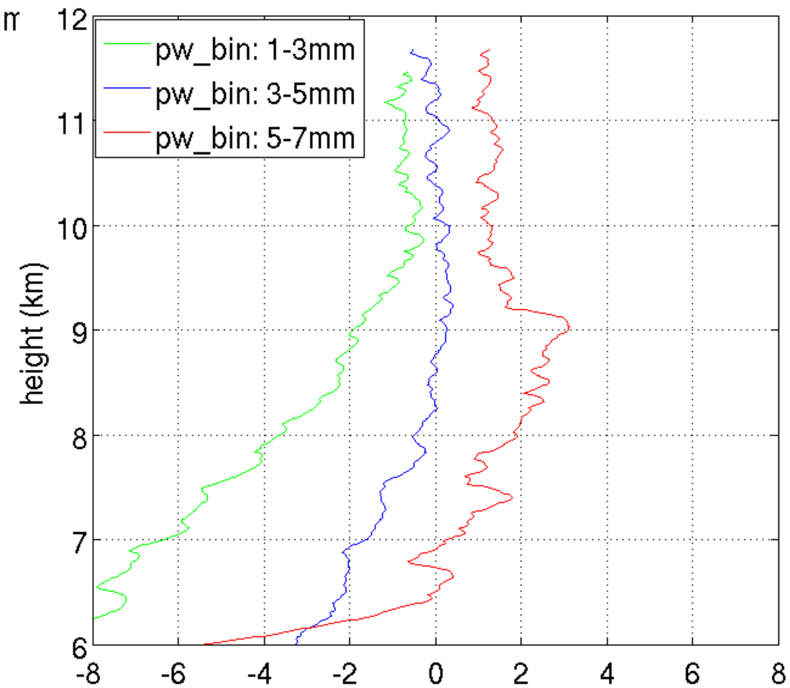
(d) RF19

- ECMWF assimilated dropsonde data
- Dropsonde doesn't sample moist storm center sampled by ARO

Spatial distribution of moisture from ARO



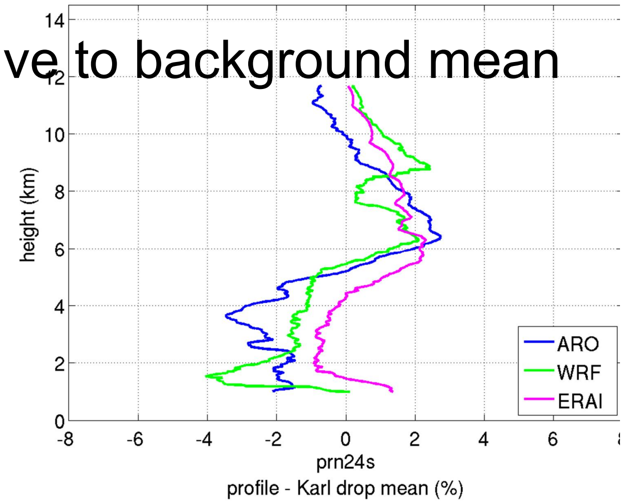
WRF PW above 500 hPa
13 Sept 12:00 UT

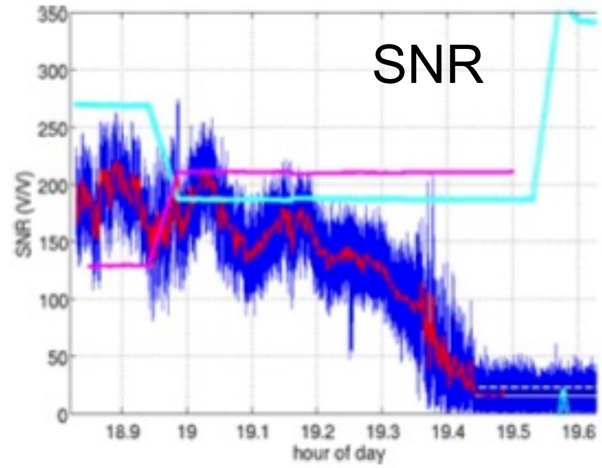


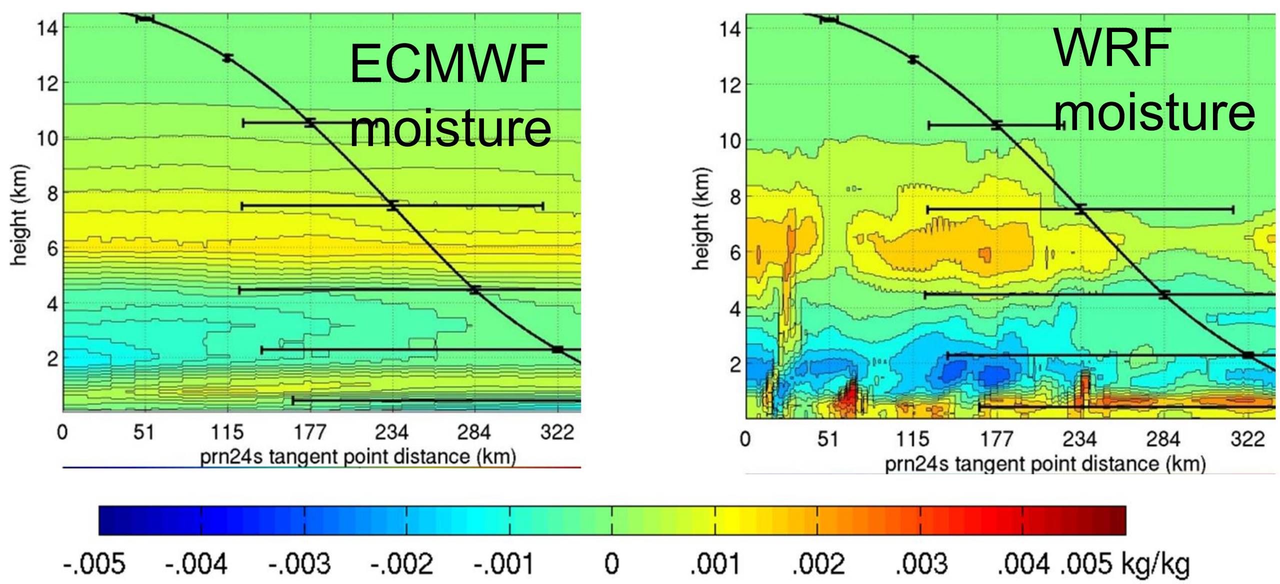
refractivity (N units)
relative to environmental
background mean

- Field campaigns are always limited in sampling distribution so mean profiles don't necessarily indicate evolution
- ARO helps by providing more profiles
- However the true benefit will come from assimilating the information at the location of each observation

Future use of ARO data in high resolution models



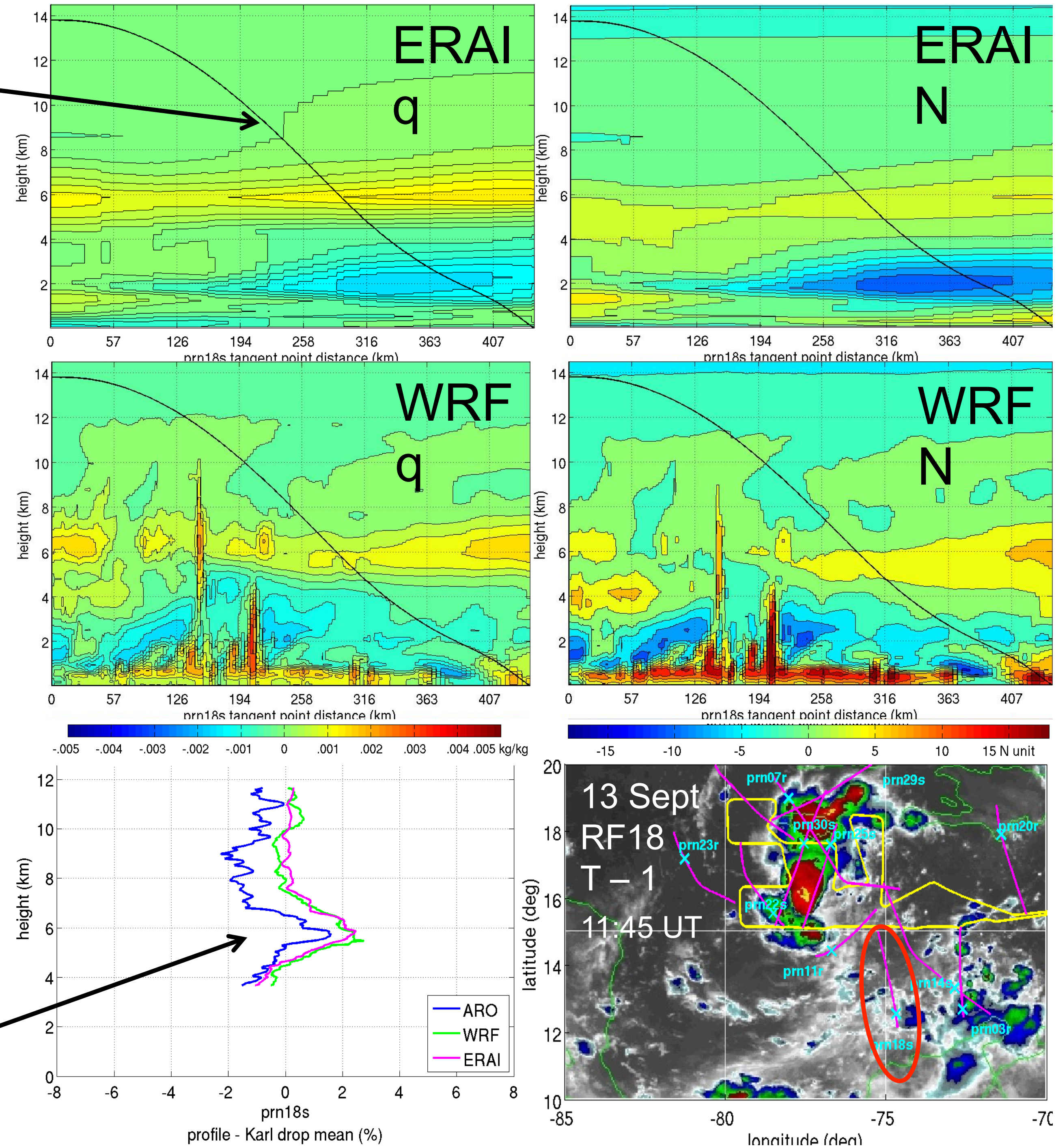




- 3D assimilation operator accounts for horizontal variation
- Assimilation tests are underway (Shu-Hua Chen UC Davis)

prn18 tangent point path

- Model N variations correspond to moisture variations
- ARO refractivity shows the same interesting high moisture at 6 km as seen in models



Refractivity minus environmental mean

Conclusions

- In the tropical environment sampled during PREDICT, dropsondes show that refractivity variations below 10 km are a good proxy for moisture and are on the order of ~5-10%.

- ARO agrees within 2% of dropsondes and NWP model output in the 6 – 12 km height range, sufficient to sense large moisture variations. Recent improvements using the phase matching retrieval technique reduce biases significantly below 6 km.

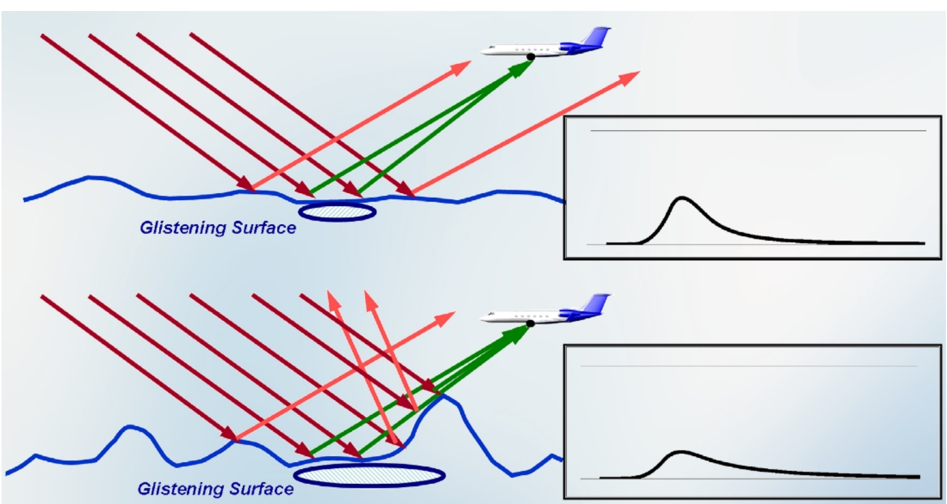
- ARO sampling is complementary to dropsondes, particularly for measuring to the side of the aircraft, and double the available profiles (10-15 per mission).

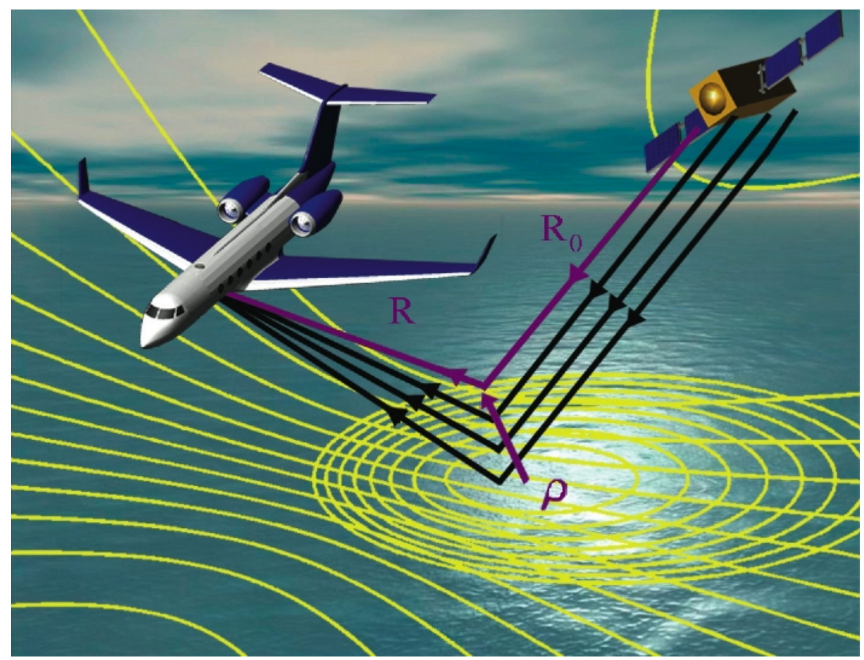
- The highest variability in moisture profiles is at mid-levels, and both dropsonde and ARO refractivity/moisture variations indicate a significant decrease in mid-level moisture that corresponds to a delay in the development of hurricane Karl.

- The ARO data set, using our quantified error characteristics, are now being assimilated into the WRF model to examine the impact of ARO data on forecasts of intensity for Karl by collaborators at UC Davis.

Ocean Reflection

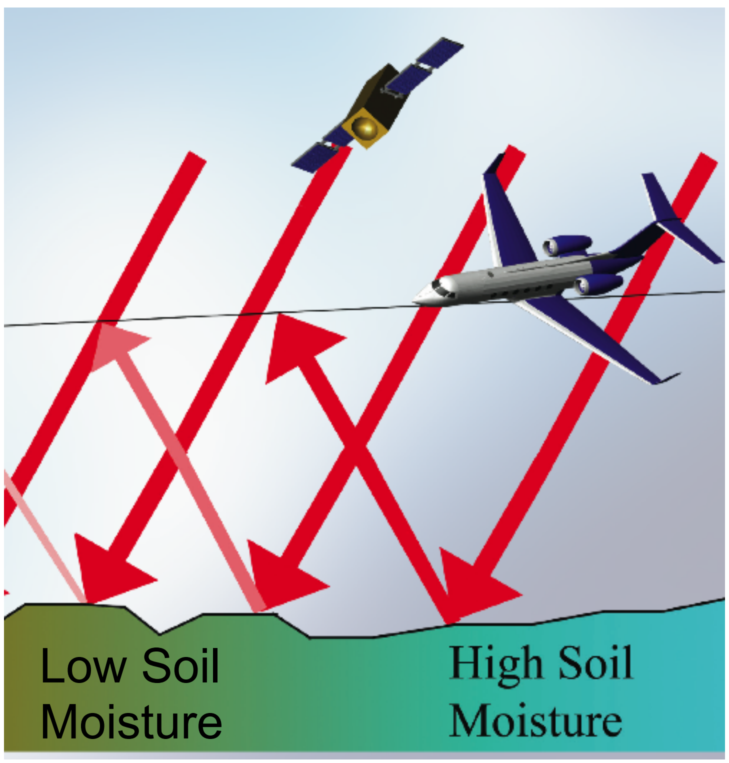
- Down-looking GPS receiver records raw reflected signal from ocean
- Delay-doppler mapping of cross-correlation function gives surface roughness
- Surface wind speed is derived from the surface roughness

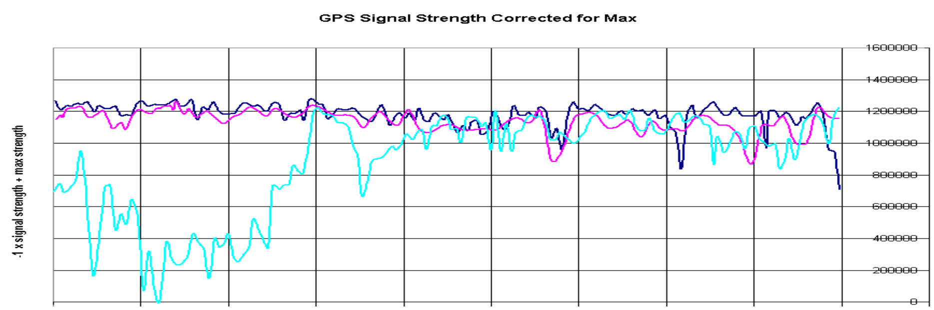


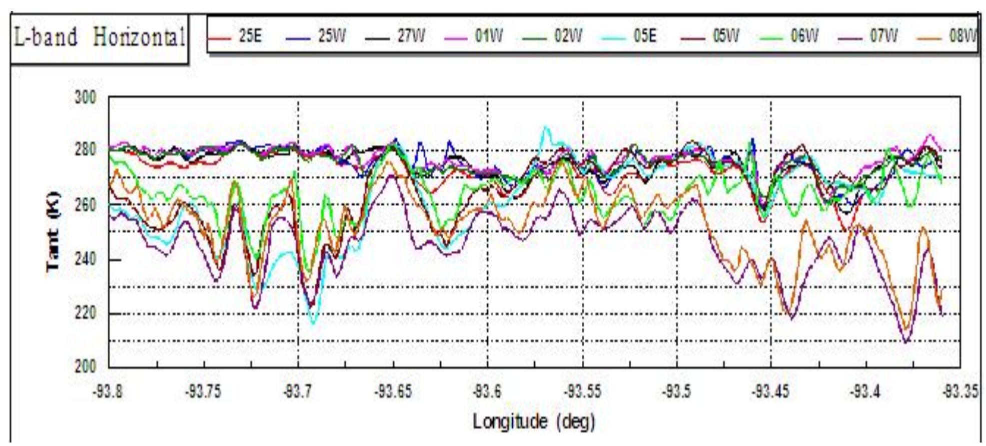


Land Reflection

- Down-looking GPS receiver records raw reflected signal from land surface
- Total power of scattered signal is related to the dielectric constant of the reflecting surface
- Soil moisture is derived from the dielectric constant

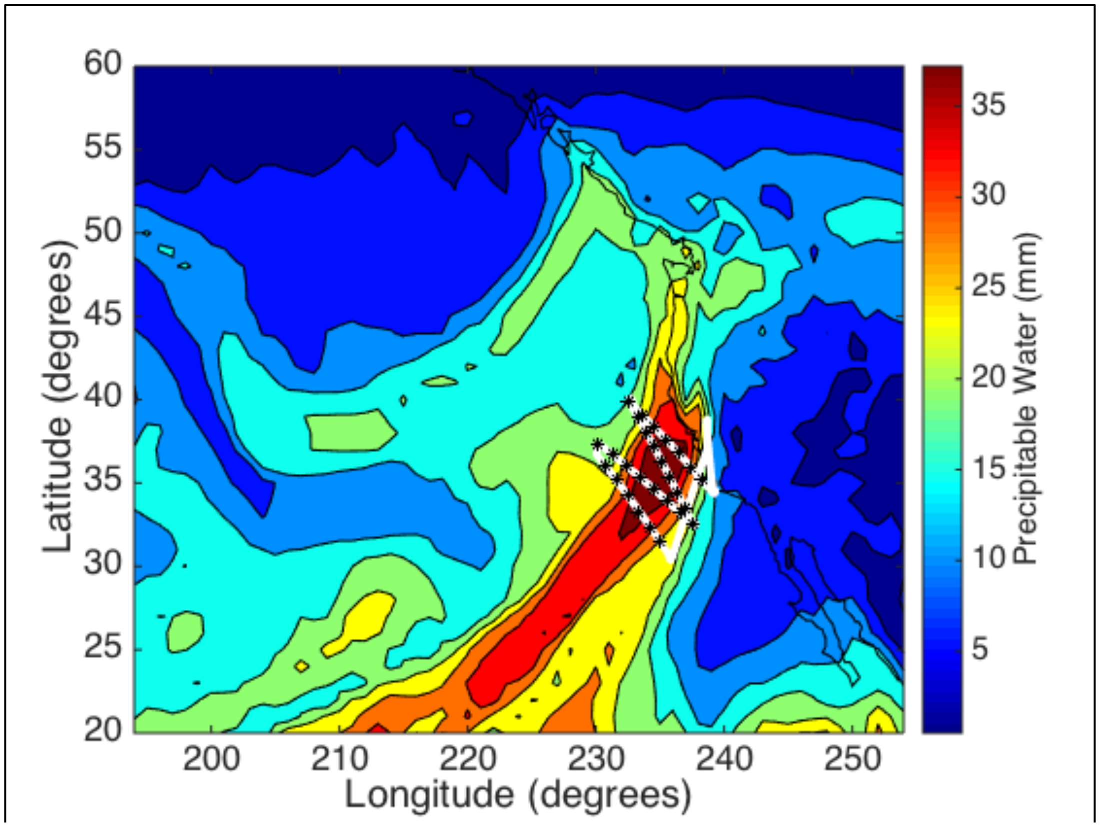






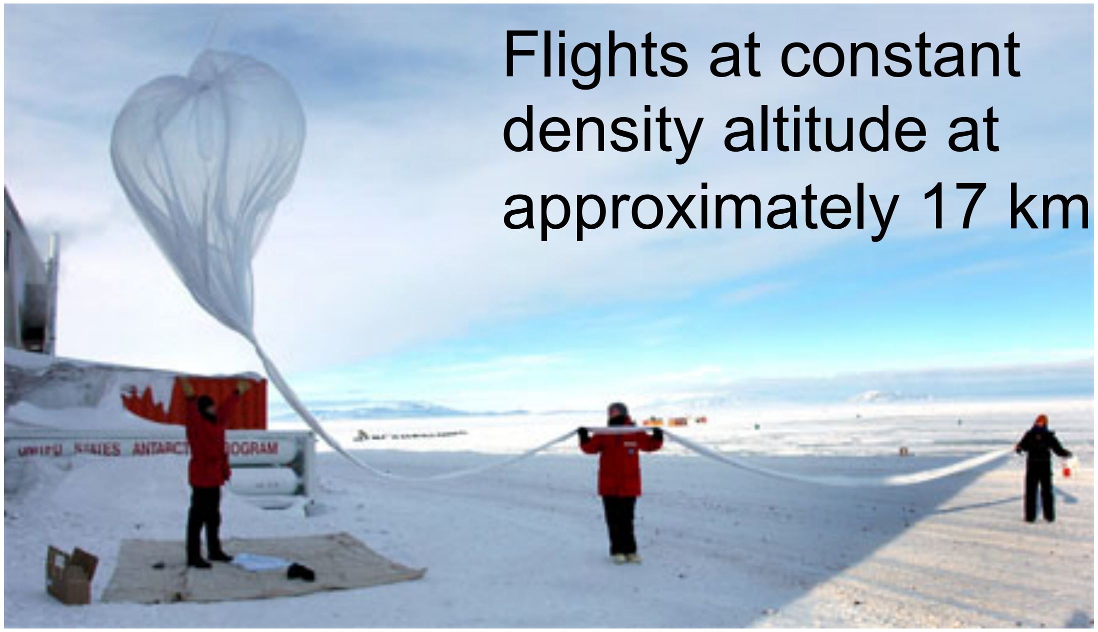
GISMOS atmospheric rivers

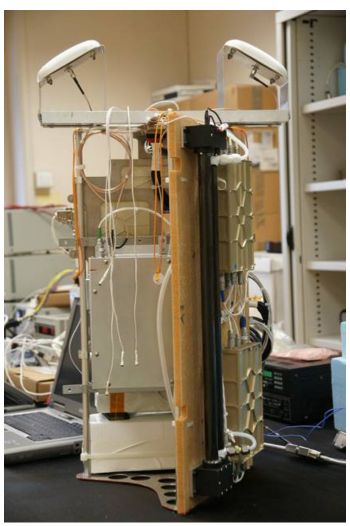
Total Precipitable Water & Flight Track



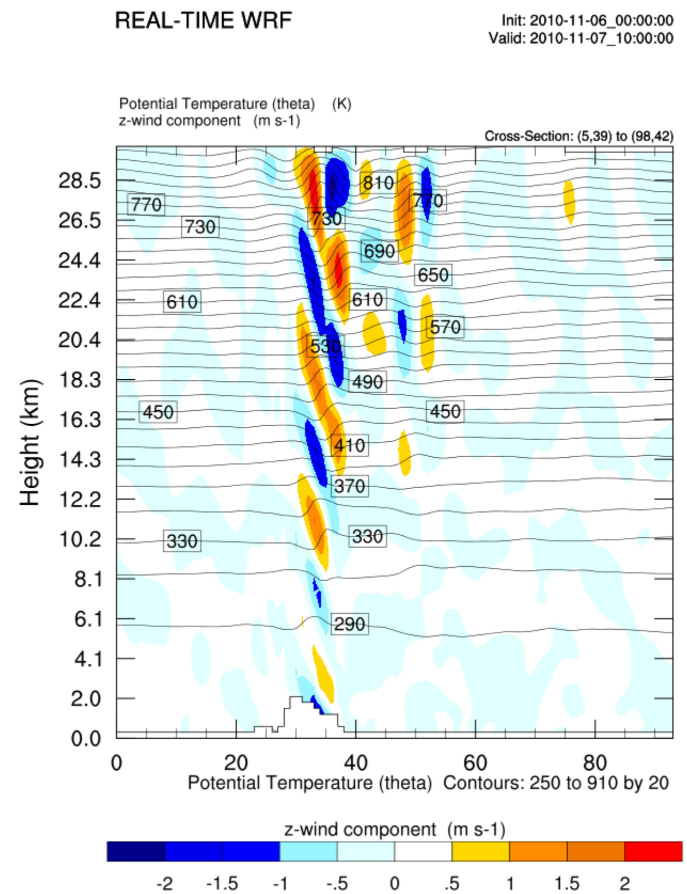
- CALWATER 2015
- NOAA and Department of Water Resources
- ARO observations of onshore moisture transport in atmospheric rivers
- Polarimetric observations to attempt retrievals of heavy precipitation

Superpressure Balloon Platform

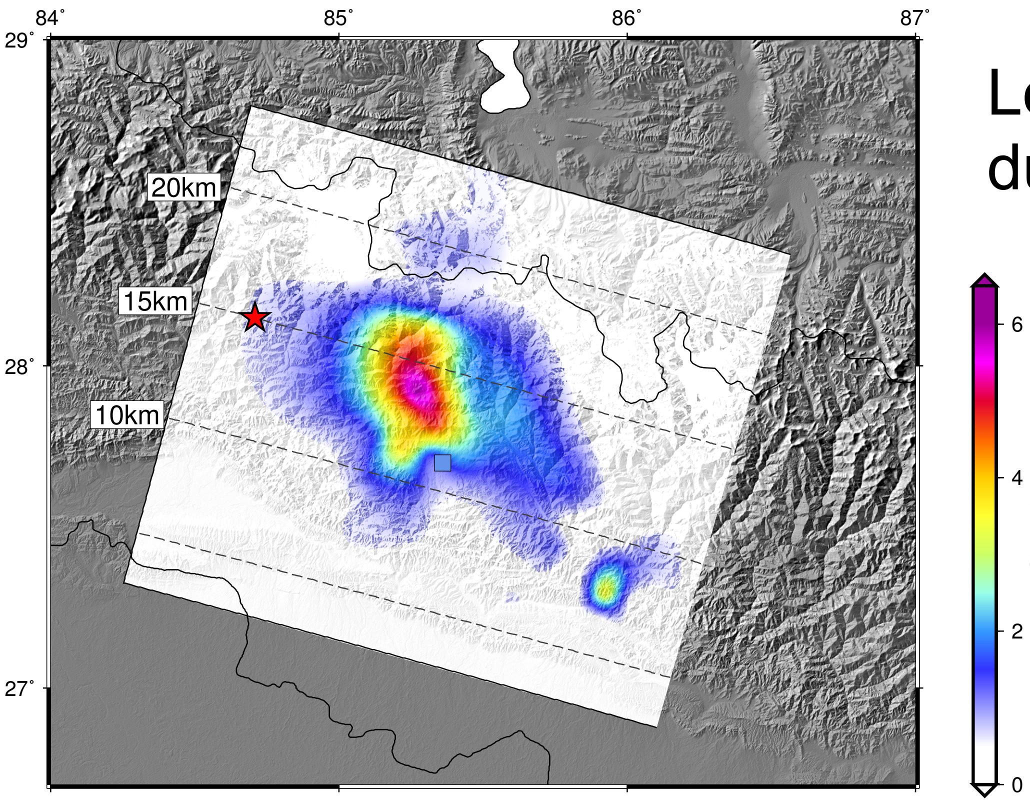




- Measure gravity wave momentum flux from balloon position and occultations
- Improve models of atmosphere-sea ice interaction

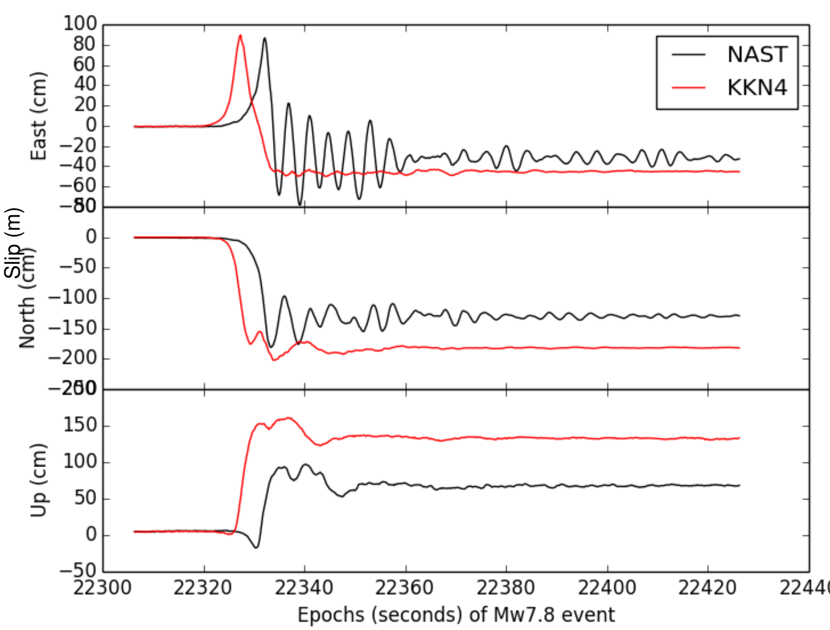


M 7.8 Nepal earthquake long period earthquake ground motions and source inversions



Source rupture based on high-rate GPS ground motions

Long period site resonances due to sedimentary basin



New & Continuing Research Areas

- GISMOS ARO hurricane data assimilation
- GISMOS ocean reflection (CYGNSS)
- Airborne soil moisture
- ARO Atmospheric rivers precipitation
- Superpressure balloon observations in Antarctic and equatorial stratosphere
- Ground-based GPS PW (UC Mexus)
- High rate terrestrial GPS for earthquake ground motions (EEW and structural monitoring)