Penn State Center for
Advanced Data Assimilation and Predictability Techniques

PENNSTATE

Advanced Convection-permitting Assimilation of All-sky Satellite Radiances for Hurricane Prediction

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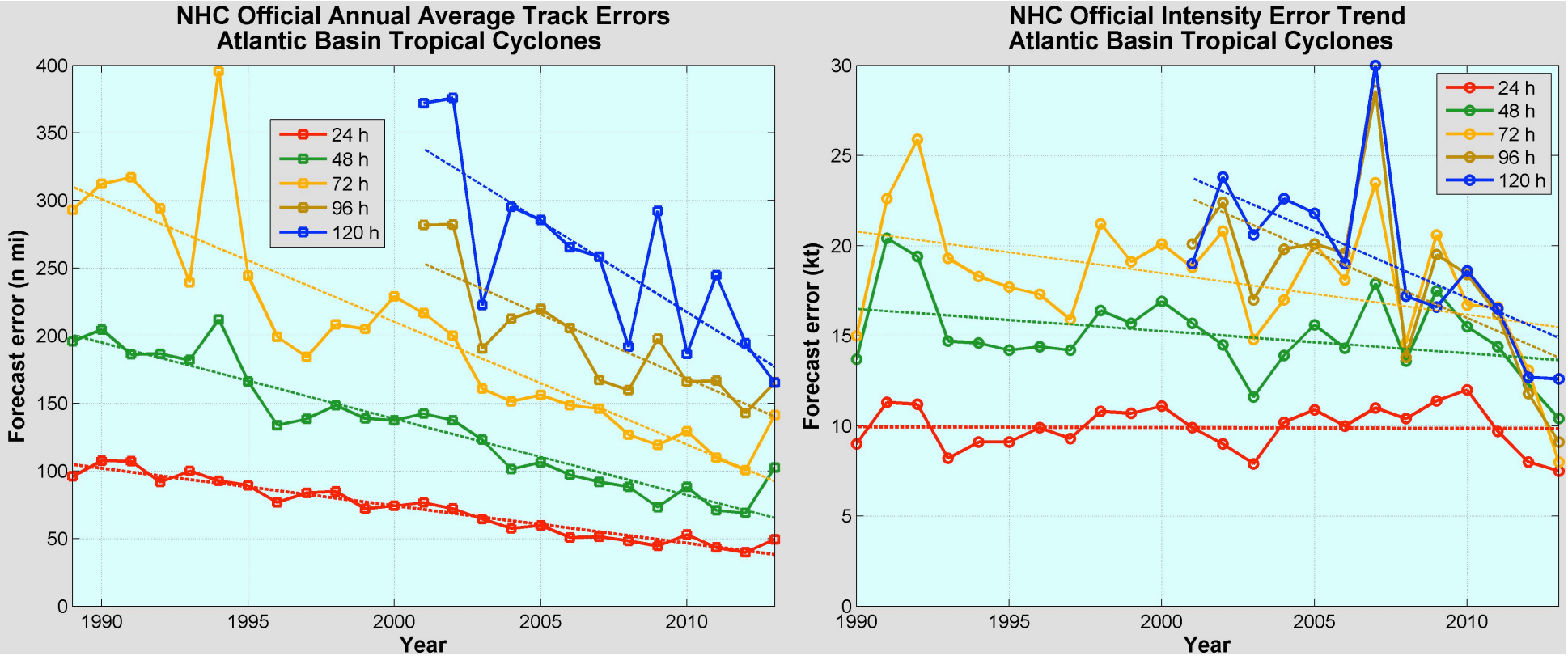
Zhang Group 2017

National Hurricane Center Official TC Forecast Errors

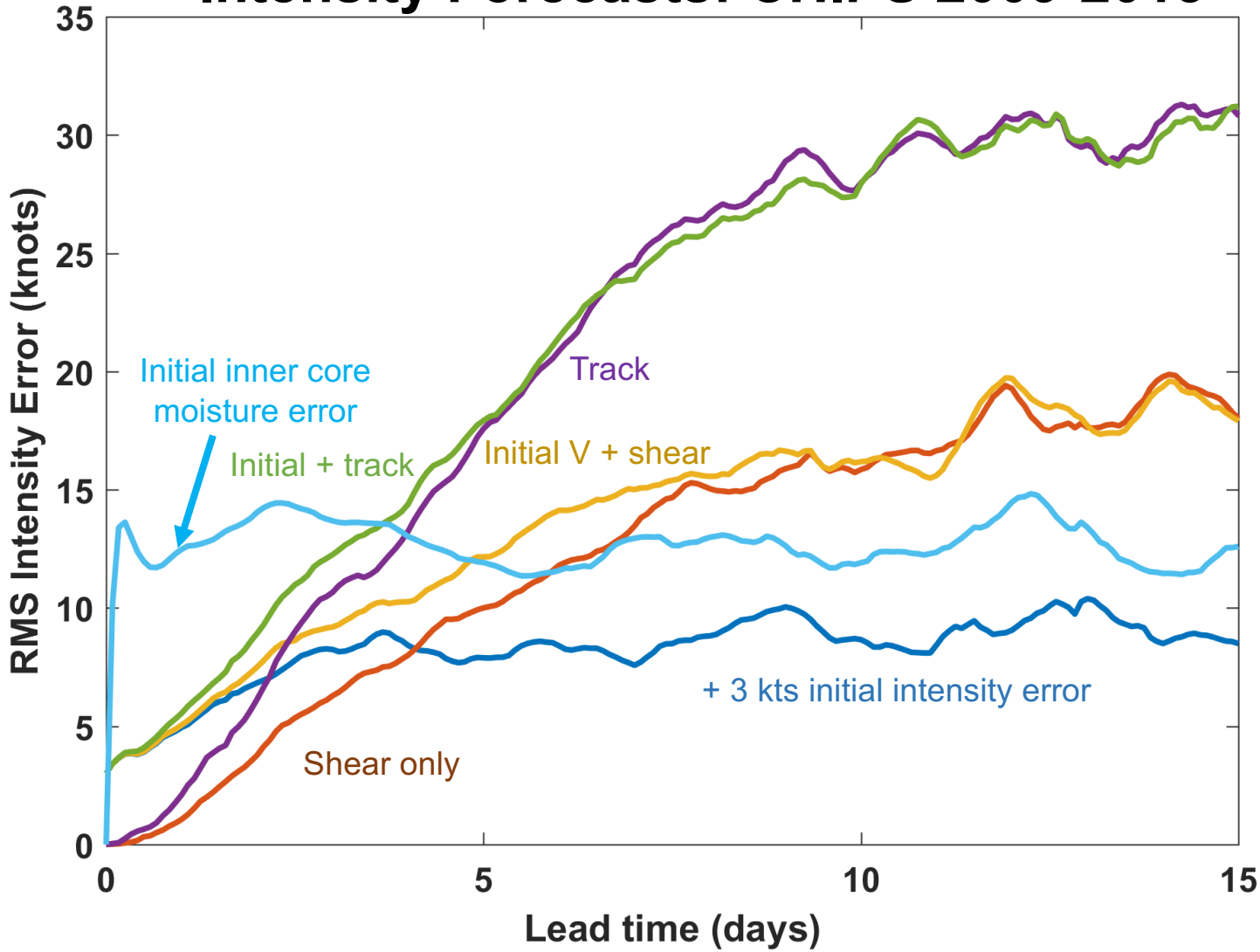


Track forecasts have improved drastically over past 25 years: a 3-day forecast today is as accurate as a 1-day forecast was in 1989.

Intensity forecast accuracy has remained generally stagnant over that same period of time, except for the last few years.

What limits the predictability of tropical cyclone intensity?

Predictability and Error Sources of Tropical Cyclone Intensity Forecasts: CHIPS 2009-2015



(Emanuel and Zhang 2016 JAS; Emanuel and Zhang 2017 JAS)

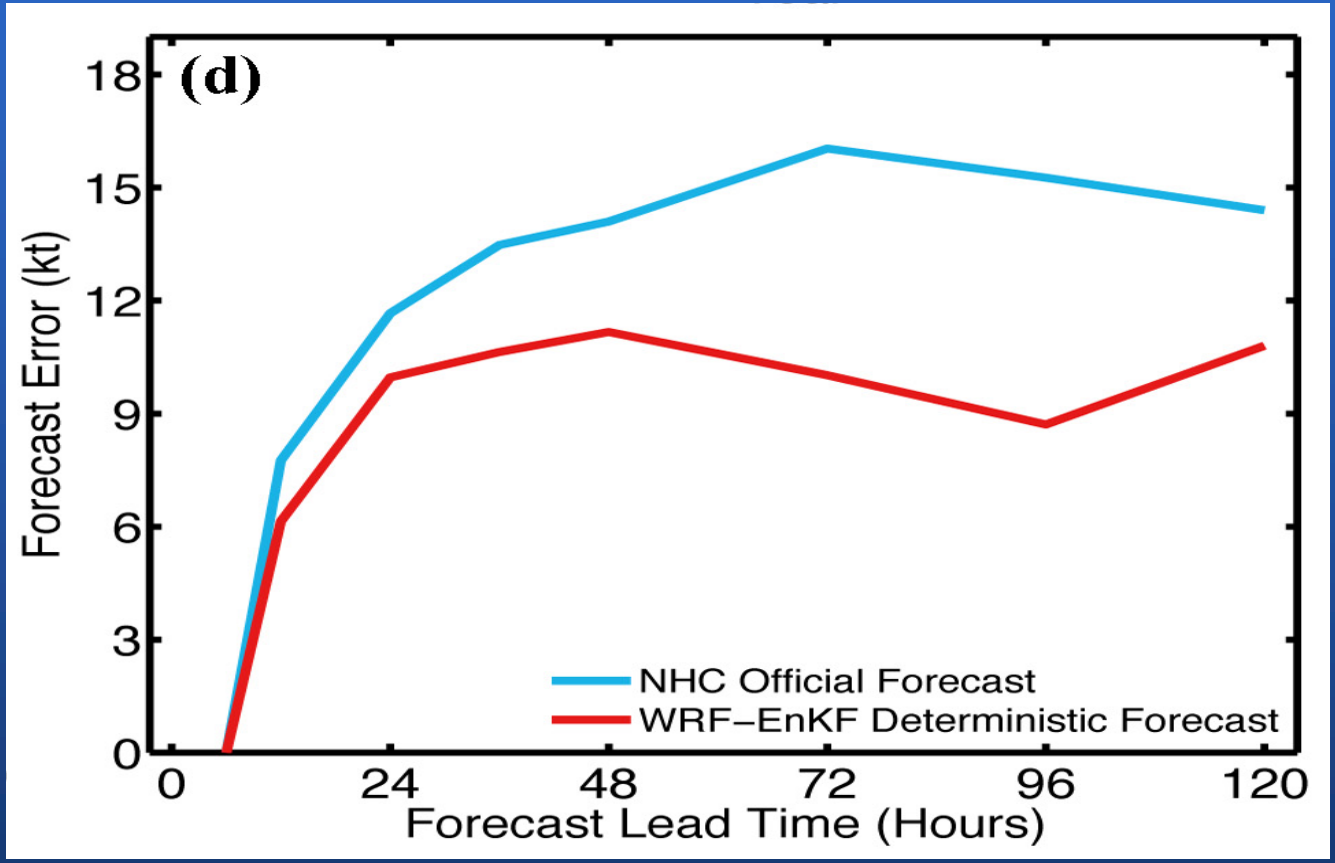
WRF-EnKF Performance Assimilating Airborne Vr

all 100+ P3 TDR missions during 2008-2012

Quasi-operational evaluation by NOAA/NHC since 2011 as stream 1.5 run

WRF-EnKF: 3 domains (27, 9 , 3km), 60-member ensemble, PSU TC flux scheme

Intensity error (knots)



(Zhang and Weng, 2015 BAMS)

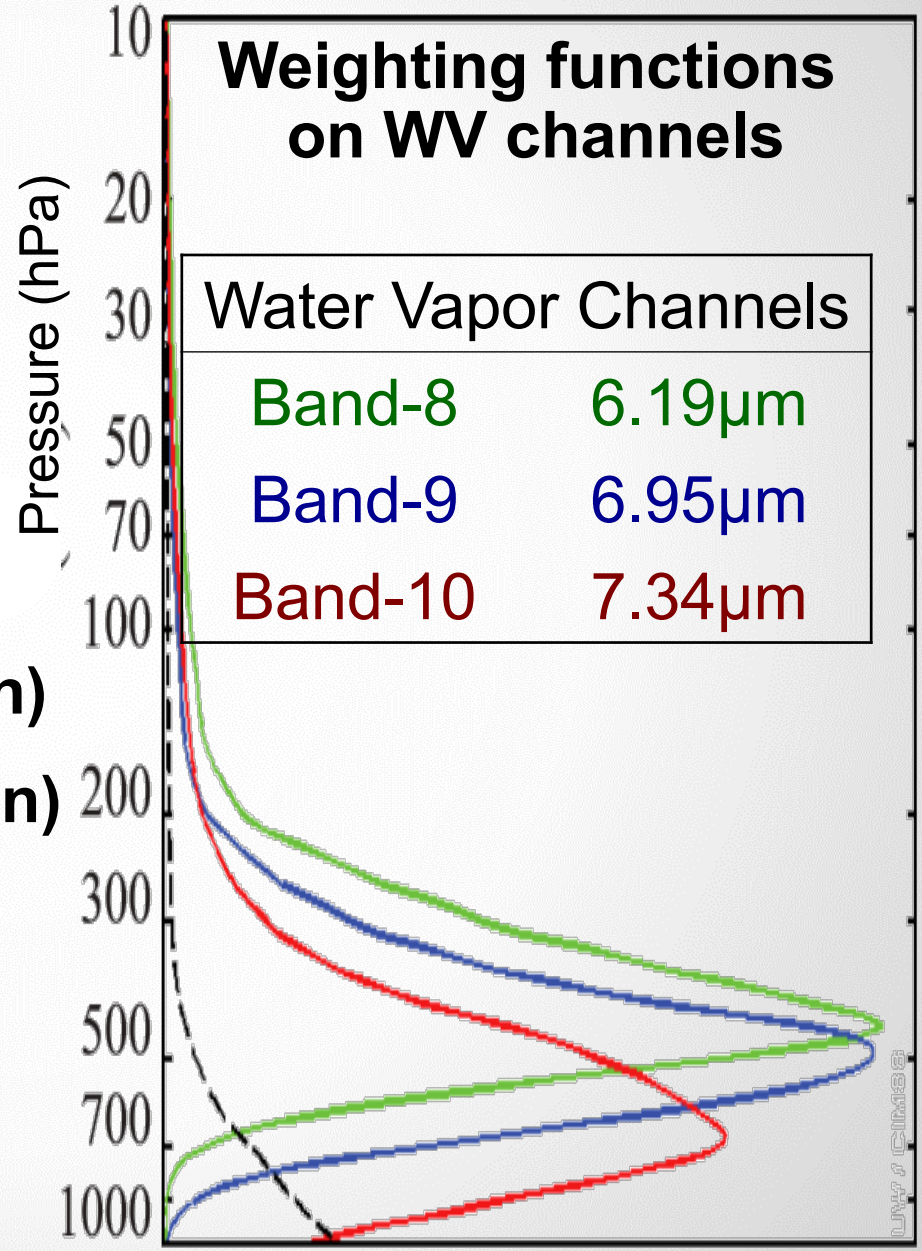
New Generation of Geostationary IR Satellites

Launch Dates:

- **Oct 2014 (Himawari-8, Japan)**
- **Nov 2016 (Himawari-9, Japan)**
- **Nov 2016 (GOES-R, USA)**
- **Dec 2016 (FY-4, China)**

High spatiotemporal resolutions:

➢ **10-15 minutes; 2-4 km**



EnKF Performance assimilating simulated radiance

Truth versus EnKF-analyzed Infrared Radiance
of GOES-R ABI ch14 (11.2 μm)

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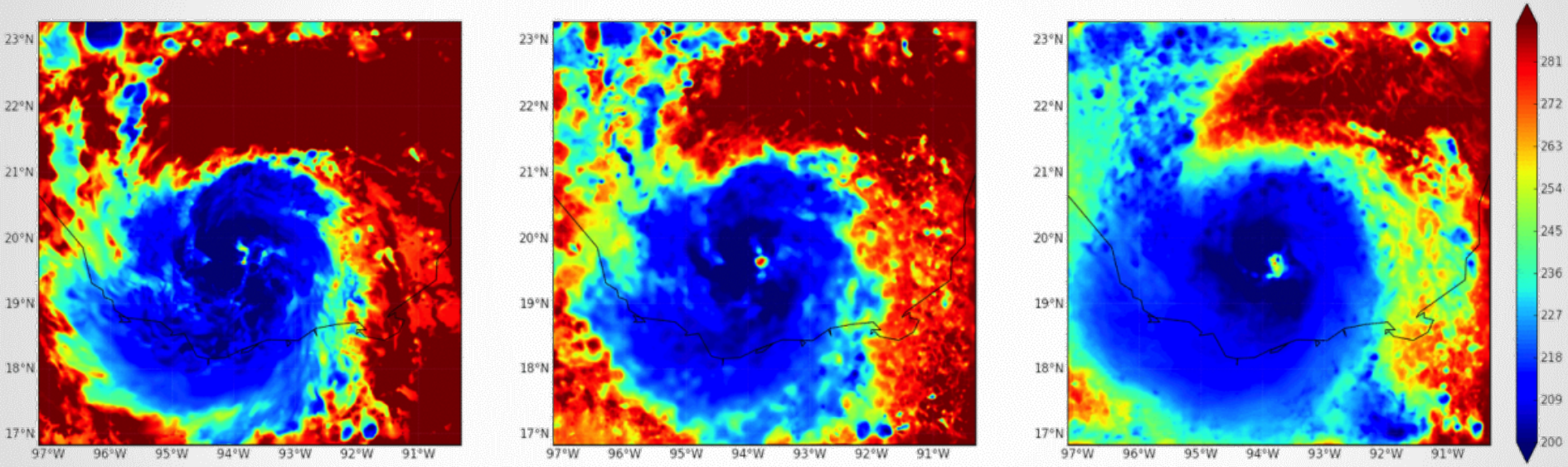


Verifying truth

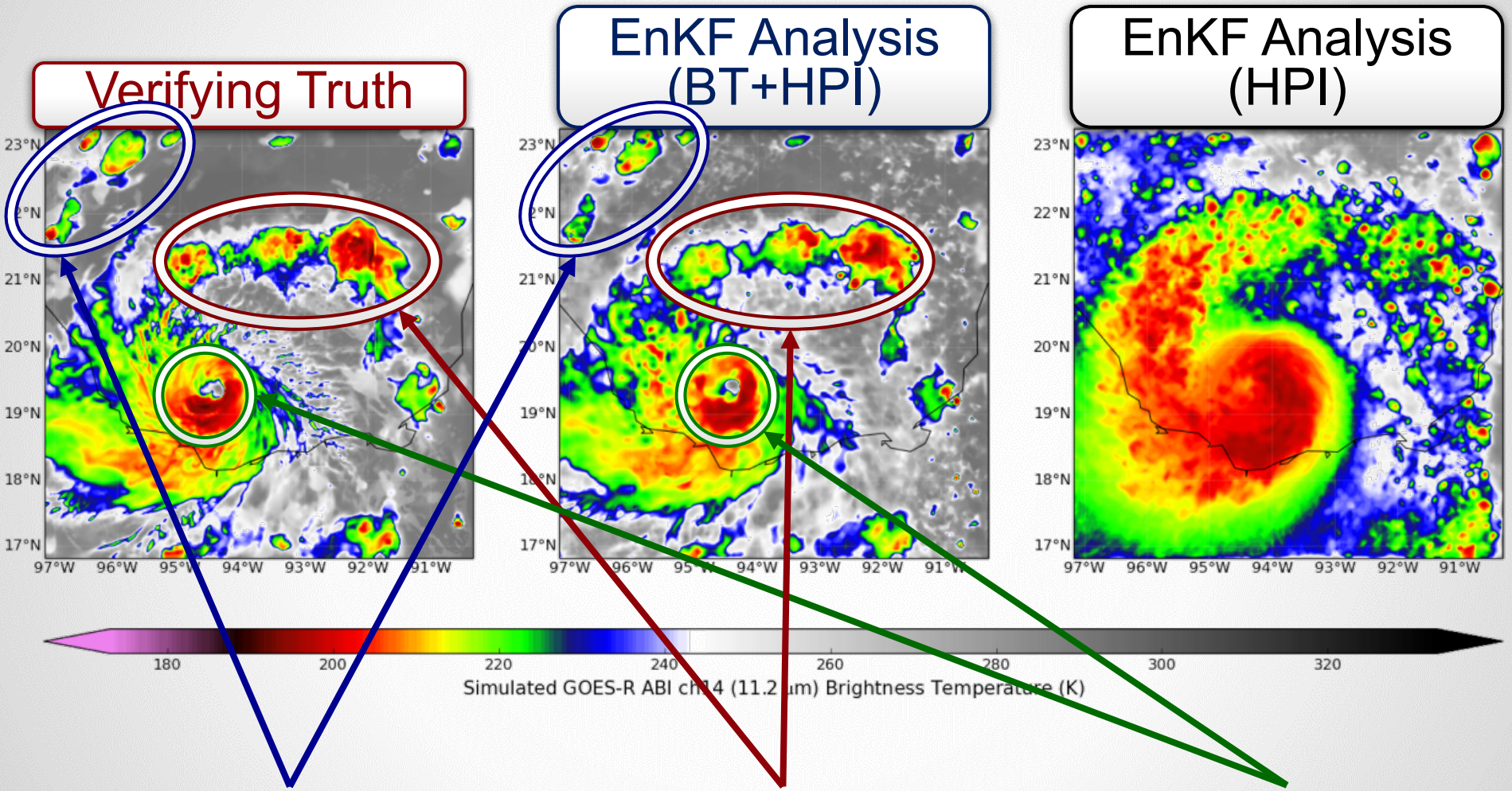
EnKF analysis with radiance & minimum SLP

EnKF analysis with minimum SLP only

(Zhang, Minamide & Clothiaux, 2016 GRL)

EnKF Performance on IR Brightness Temperature

Brightness Temperature of GOES-R ABI Ch14 (11.2 μm)



Convective cells

Primary rainband

eyewall

(Zhang, Minamide & Clothiaux, 2016 GRL)

Adaptive Observation Error Inflation (AOEI)

Problem: **erroneous analysis increments**

If **Model (clear / cloudy) ≠ Observation (cloudy / clear)**

In updating SLP, $\frac{12.5\,[hPa \times K]}{3^2 + 5^2[K^2]} \times 40[K] \sim \mathbf{15[hPa]}$

AOEI: inflating observation error variance

$$\sigma^2_{o-AOEI} = max\left\{\sigma^2_o, [y_o - h(x_b)]^2 - \sigma^2_{h(x_b)}\right\}$$

With AOEI, $\frac{12.5\,[hPa \times K]}{40^2[K^2]} \times 40[K] \sim \mathbf{0.3[hPa]}$

AOEI

suppresses erroneous analysis increments,

relieves the issues of representativeness & sampling,

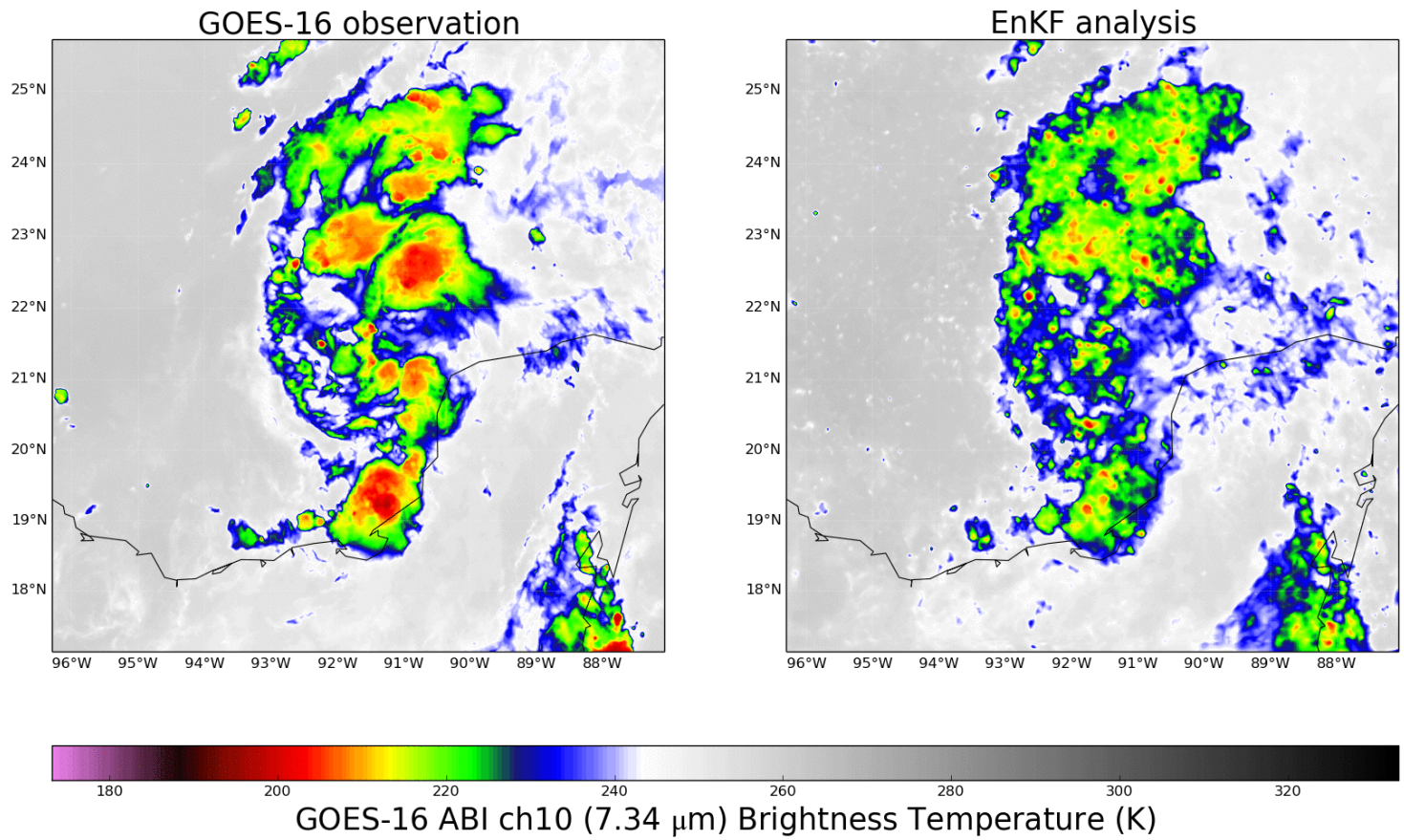
& contributes to maintaining balance.

(Minamide & Zhang, MWR, 2017)

Assimilating All-sky GOES-R Radiances: Harvey (2017)

PSU WRF-EnKF, Δx=3km, ensemble size=60, channel 8, every 1h

Independent observations vs. EnKF analysis of channel 10



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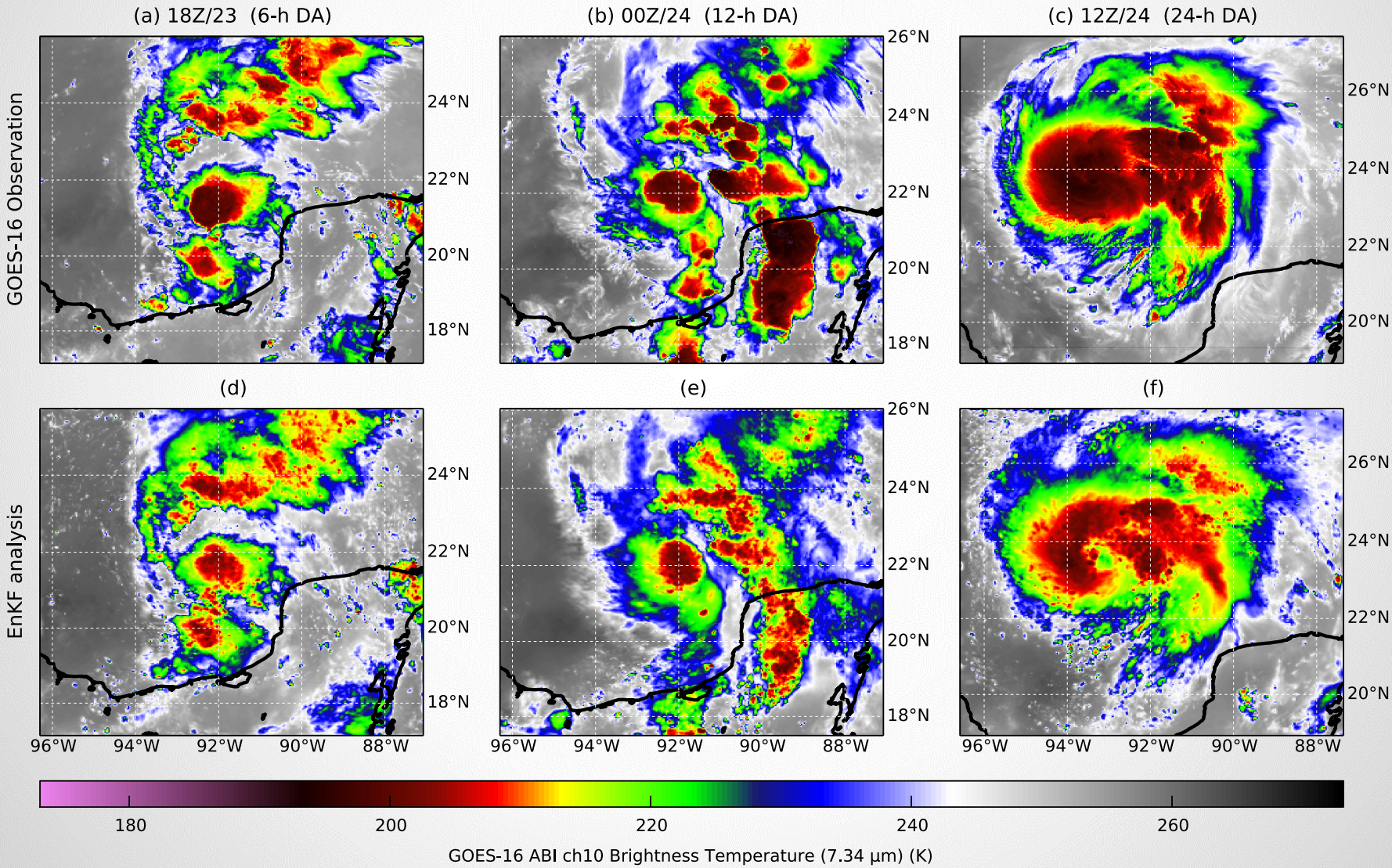
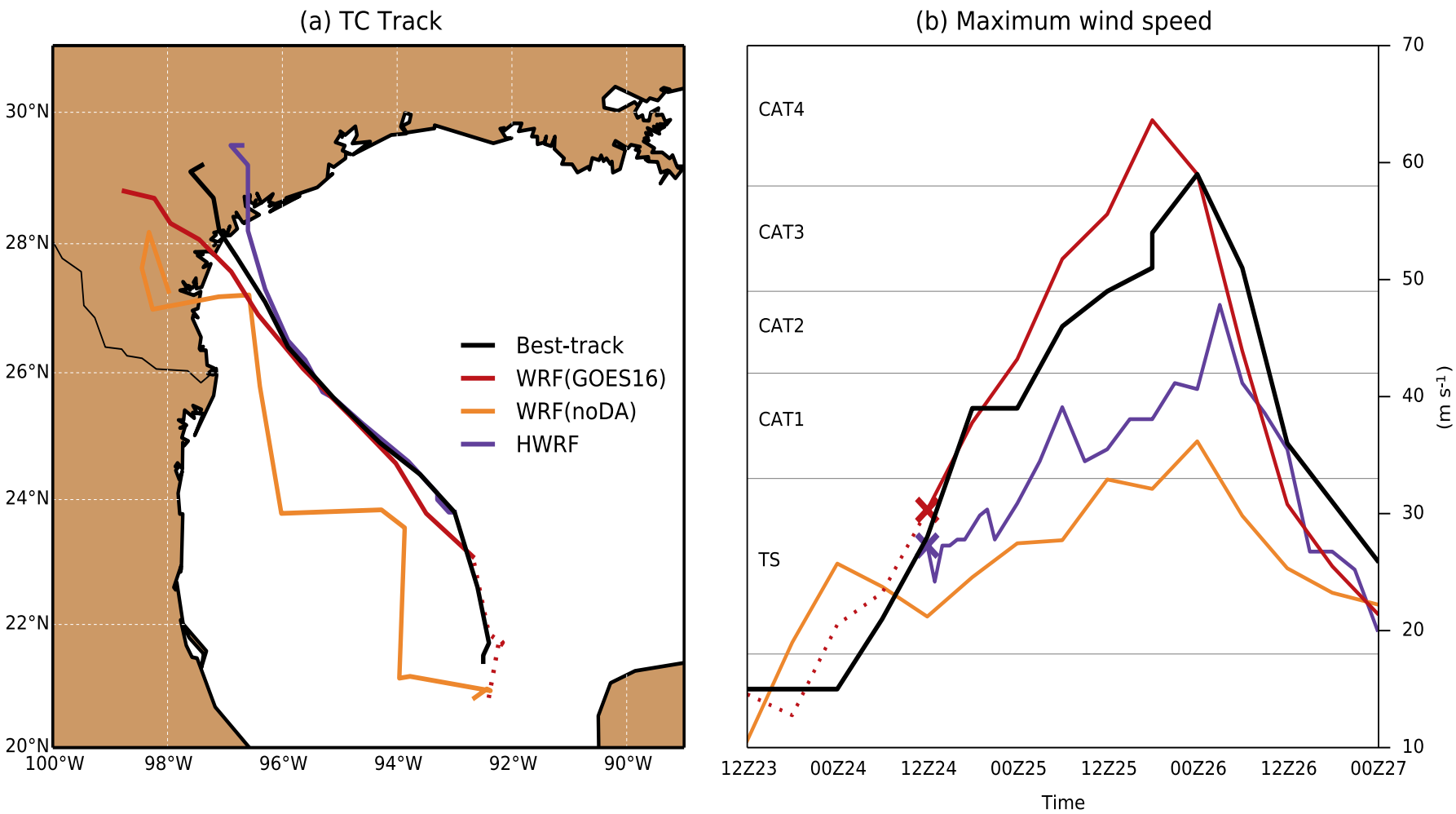
Assimilating All-sky Satellite Radiances: Harvey (2017)

Independent Observations vs. EnKF analysis

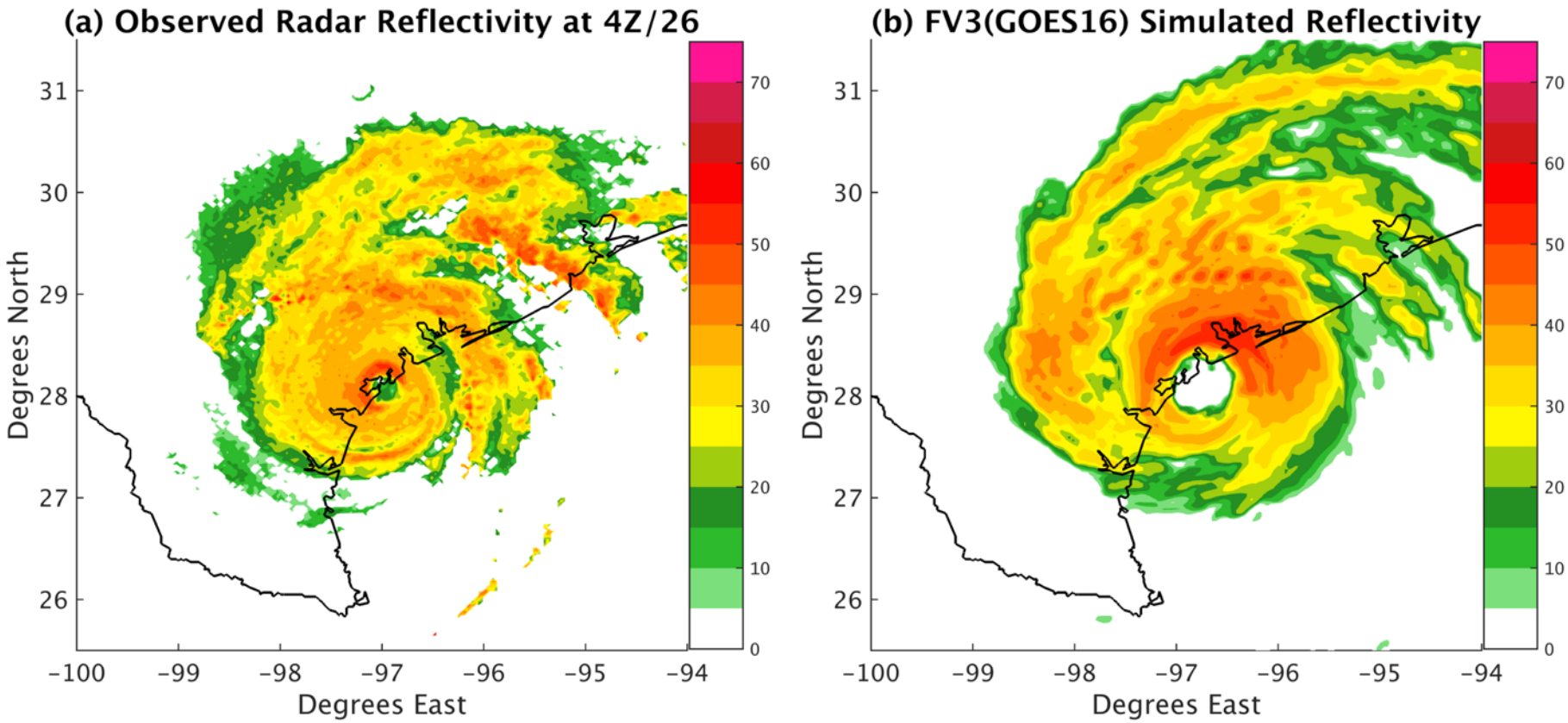


PSU WRF-EnKF Forecasts of Harvey w & w/ GOES-R



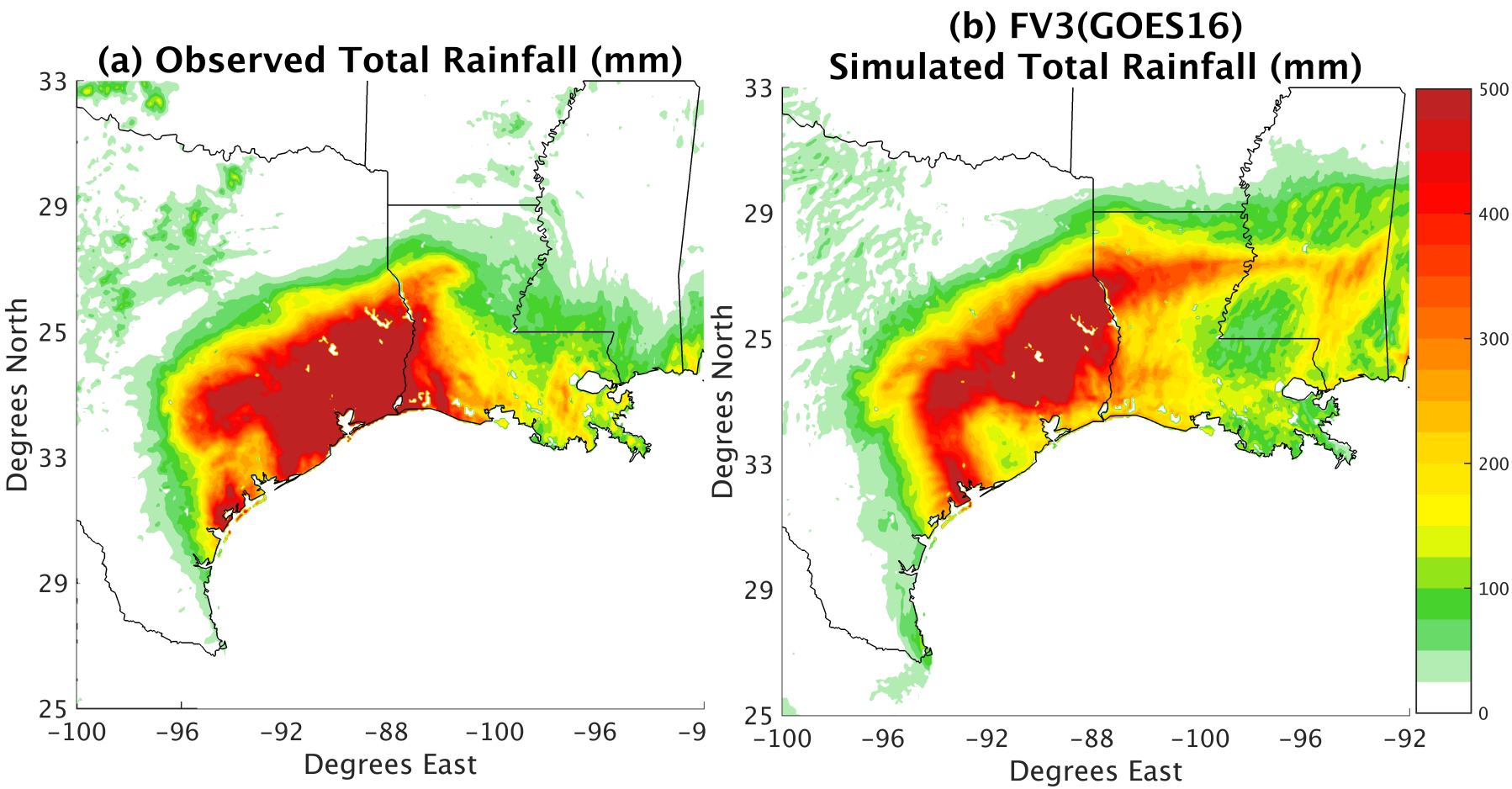
Ongoing research with M. Minamide, XC Chen, R. Nystrom

Prediction of Harvey at landfall by the FV3 model with a 3-km nest with TC vortex initialized with EnKF GOES-R assimilation



Ongoing PSU collaboration with GFDL

Prediction of Harvey (2017) with global-nested FV3 model and GOES-R assimilation



Ongoing PSU collaboration with GFDL

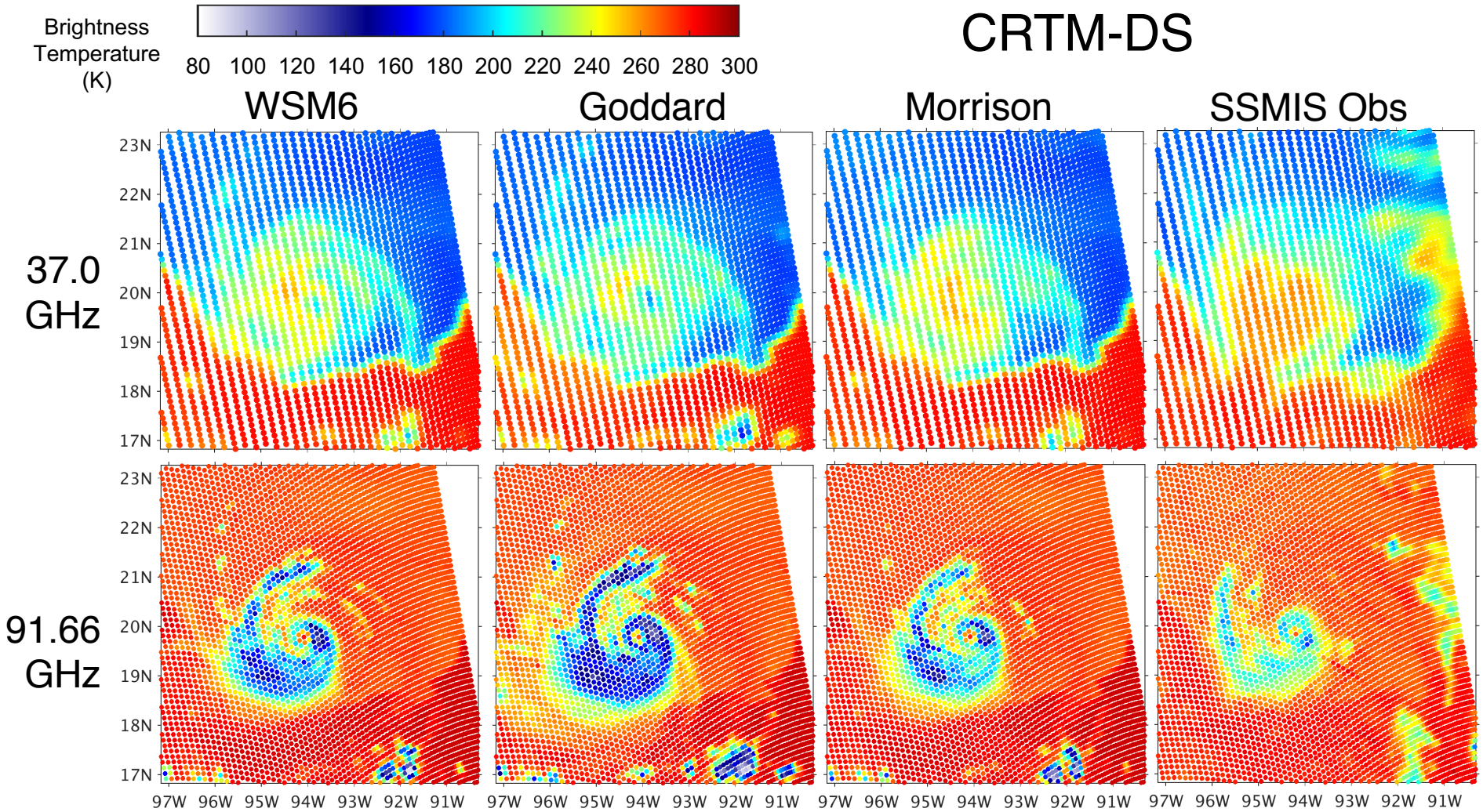
Towards Assimilation of Cloudy MW Radiances
Modifying CRTM for microphysics consistency

- "Distribution-Specific," CRTM-DS:
  - New cloud scattering property lookup tables
  - Construct with MP scheme particle properties and size distributions
    - Very high resolution (1 µm radius)

- Single particles modeled as soft spheres
  - These MP schemes specify hydrometeors as spheres
  - Maxwell-Garnett mixing formula for ice dielectric constants
  - Liquid dielectric constants from Tuner et al. (2016)

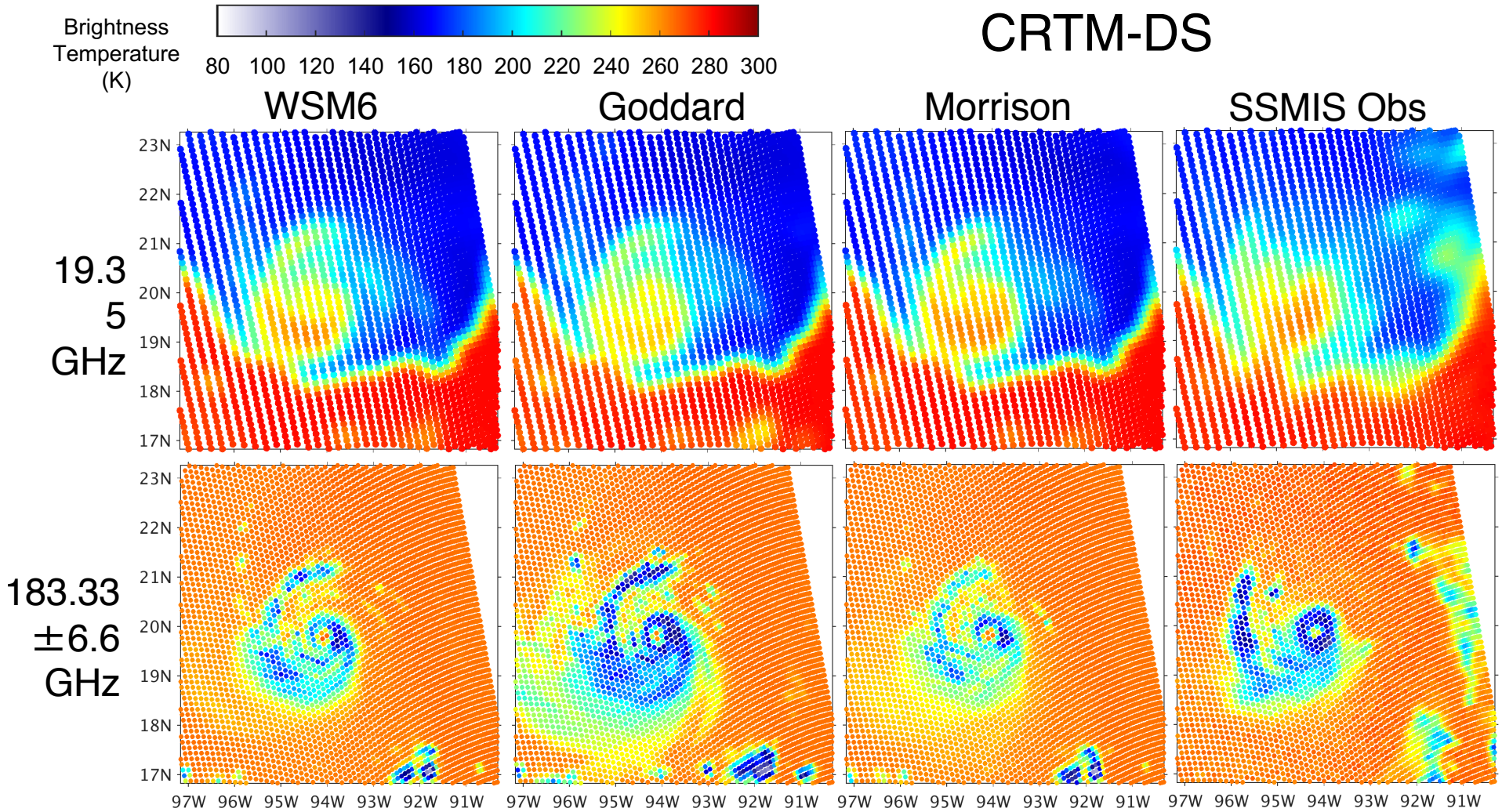
Sieron, Clothiaux, Zhang, Otkin and Lu (2017 JGR)

CRTM-Simulated vs. SSMIS-observed All-sky Radiance



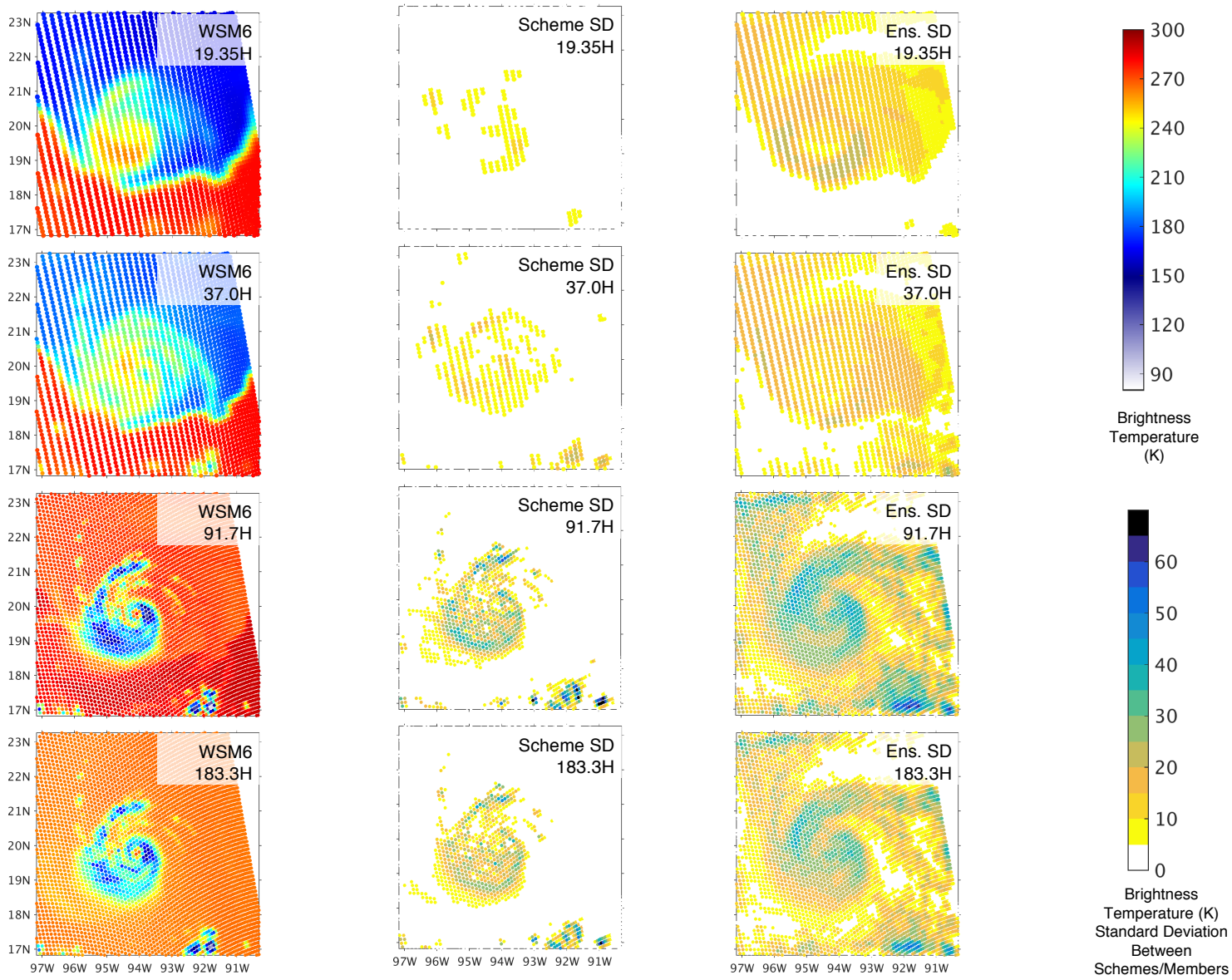
Microphysics distribution specific CRTM can help more direct inter-model comparison, and have the great promise to use vast satellite MW radiance to validate and improve model microphysics parameterizations.

CRTM-Simulated vs. SSMIS-observed All-sky Radiance



Microphysics distribution specific CRTM can help more direct inter-model comparison, and have the great promise to use vast satellite MW radiance to validate and improve model microphysics parameterizations.

CRTM Simulated: initial condition vs. physics uncertainty

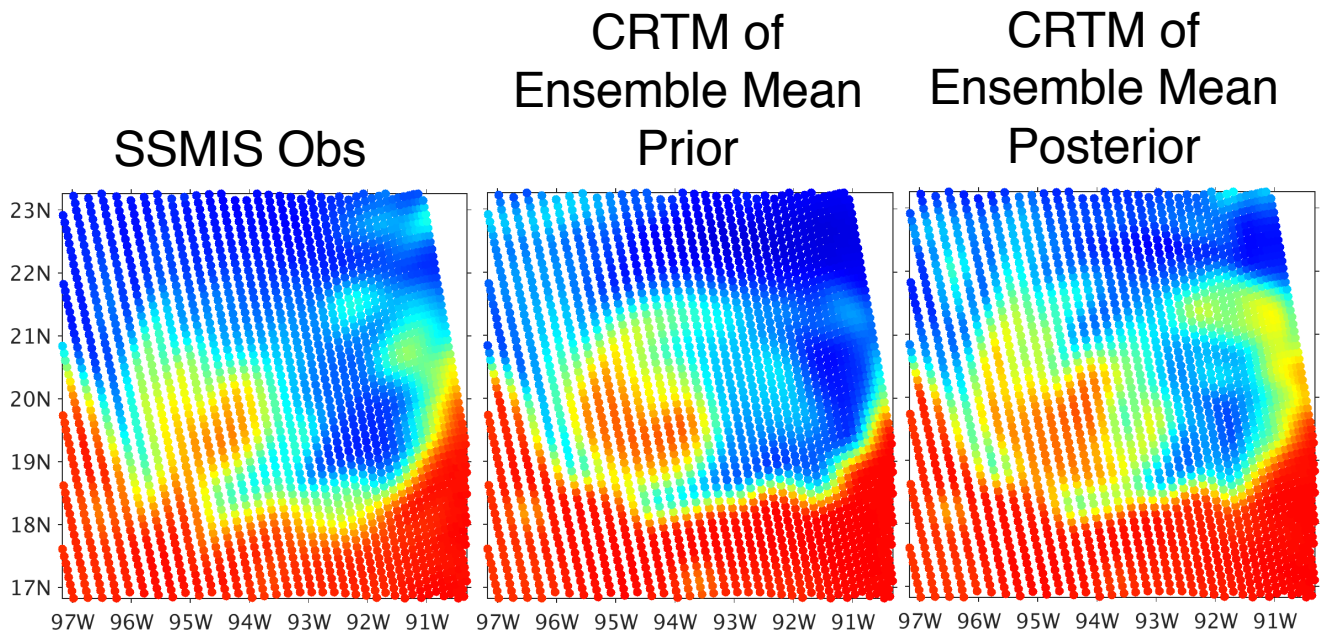


Ongoing research with Scott Sieron and Eugene Clothiaux

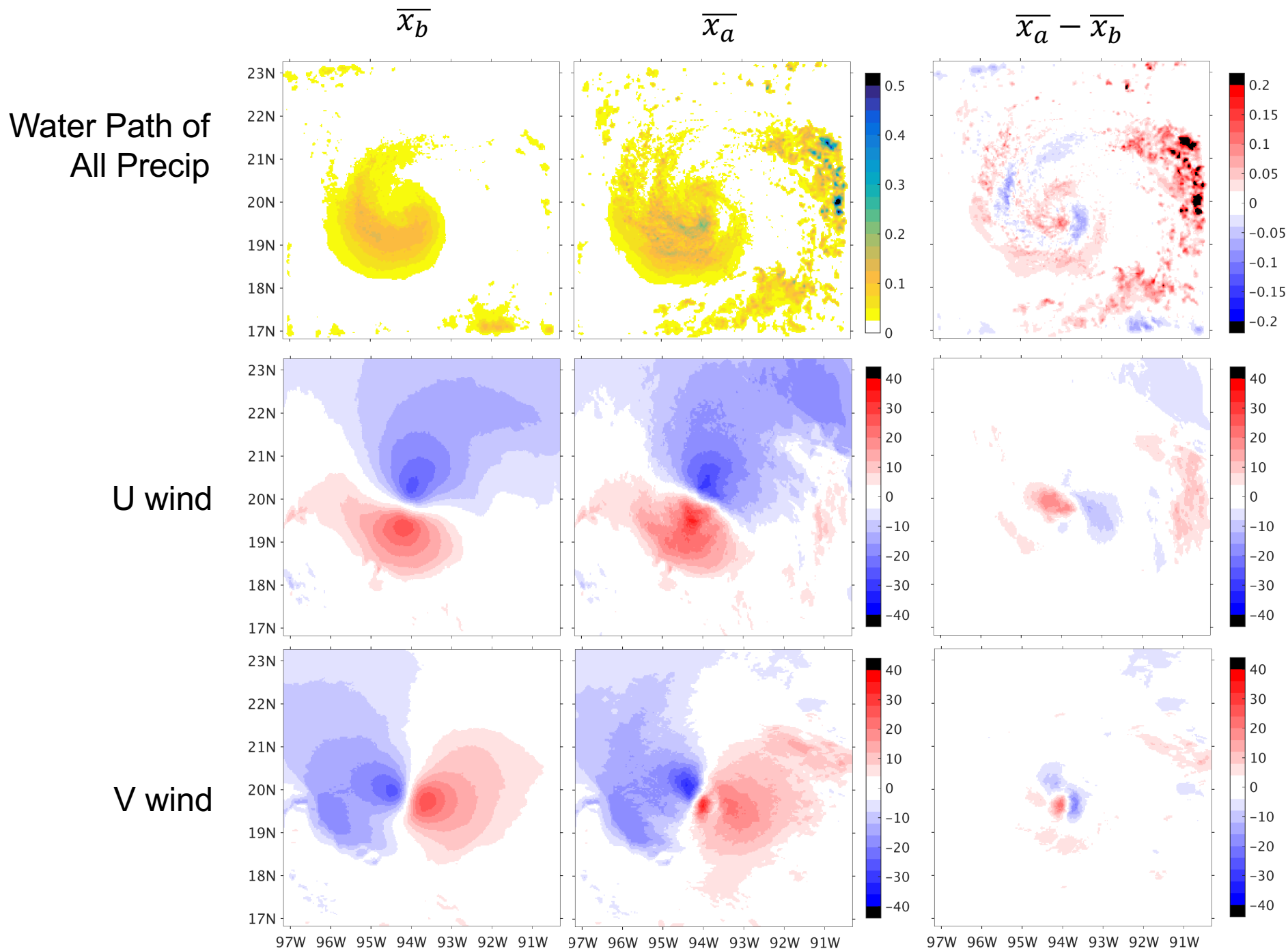
First Convection-permitting EnKF Experiment Assimilating Real-data SSMIS BTs for Karl (2010)

Prior: at 00Z/17 3-h ensemble forecast from 21Z/16 SEP 2010
WRF-EnKF, 27, 9 & 3 km (D1-D3), 60-member, AOEI, SCL, RTPP

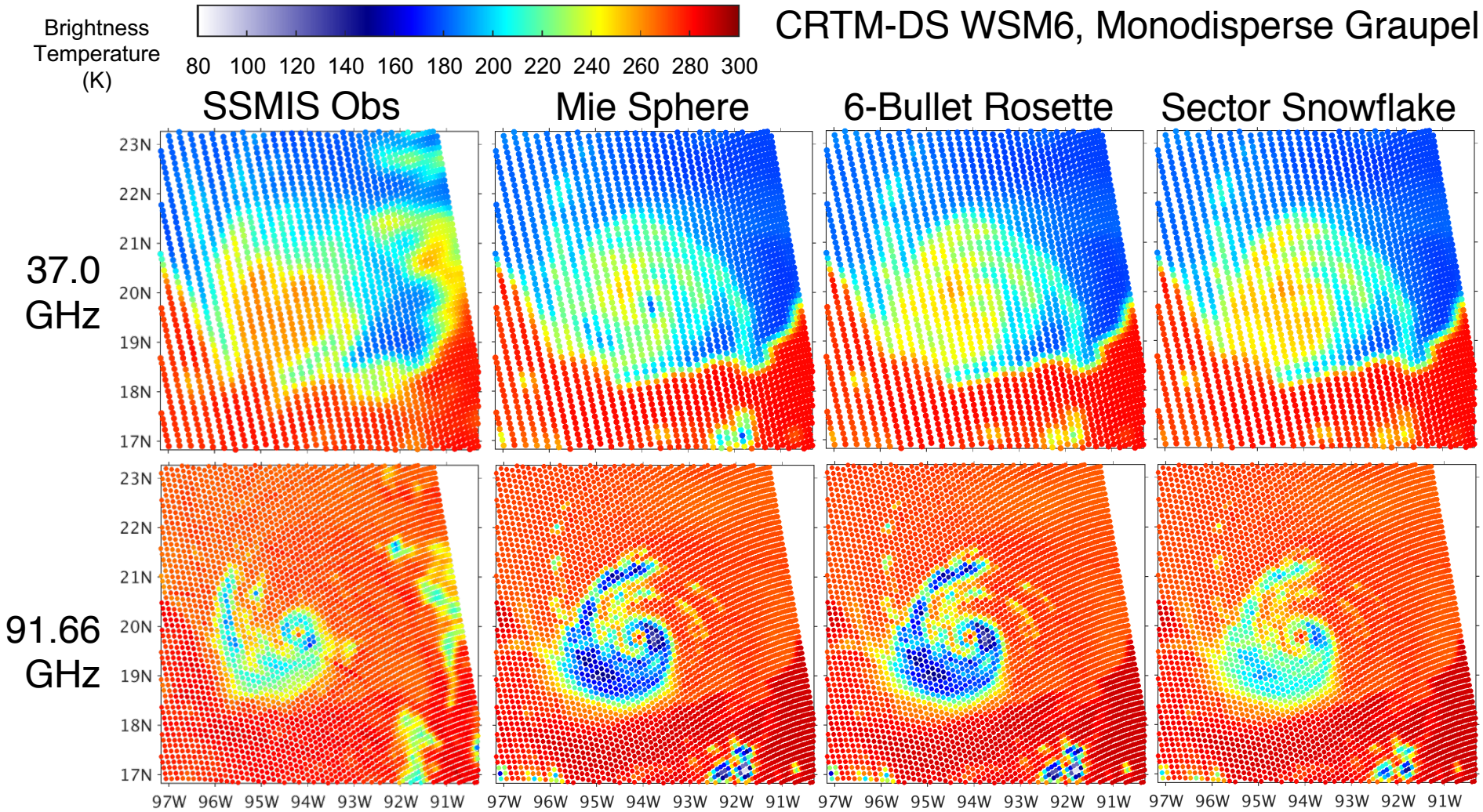
First only assimilate the 19.35-GHZ channel which is very rain sensitive



The EnKF posterior updates of the observed channel is quite promising!


$\overline{x_b}$
$\overline{x_a}$
$\overline{x_a} - \overline{x_b}$
Water Path of All Precip
U wind
V wind
23N
22N
21N
20N
19N
18N
17N
97W 96W 95W 94W 93W 92W 91W
0.5
0.4
0.3
0.2
0.1
0
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
40
30
20
10
0
−10
−20
−30
−40

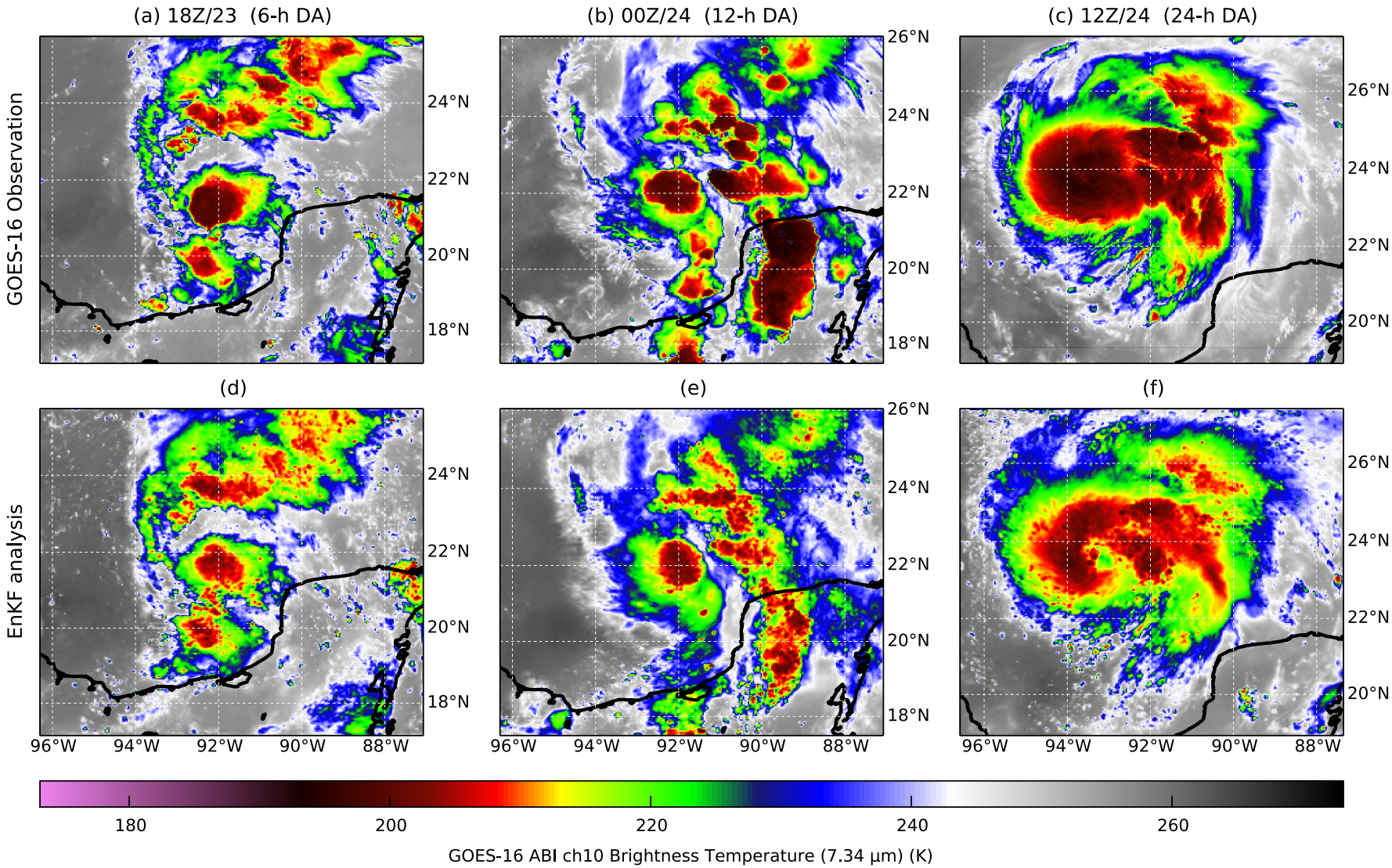
CRTM-Simulated vs. SSMIS-observed: non-spherical?



Ongoing research with Scott Sieron and Eugene Clothiaux

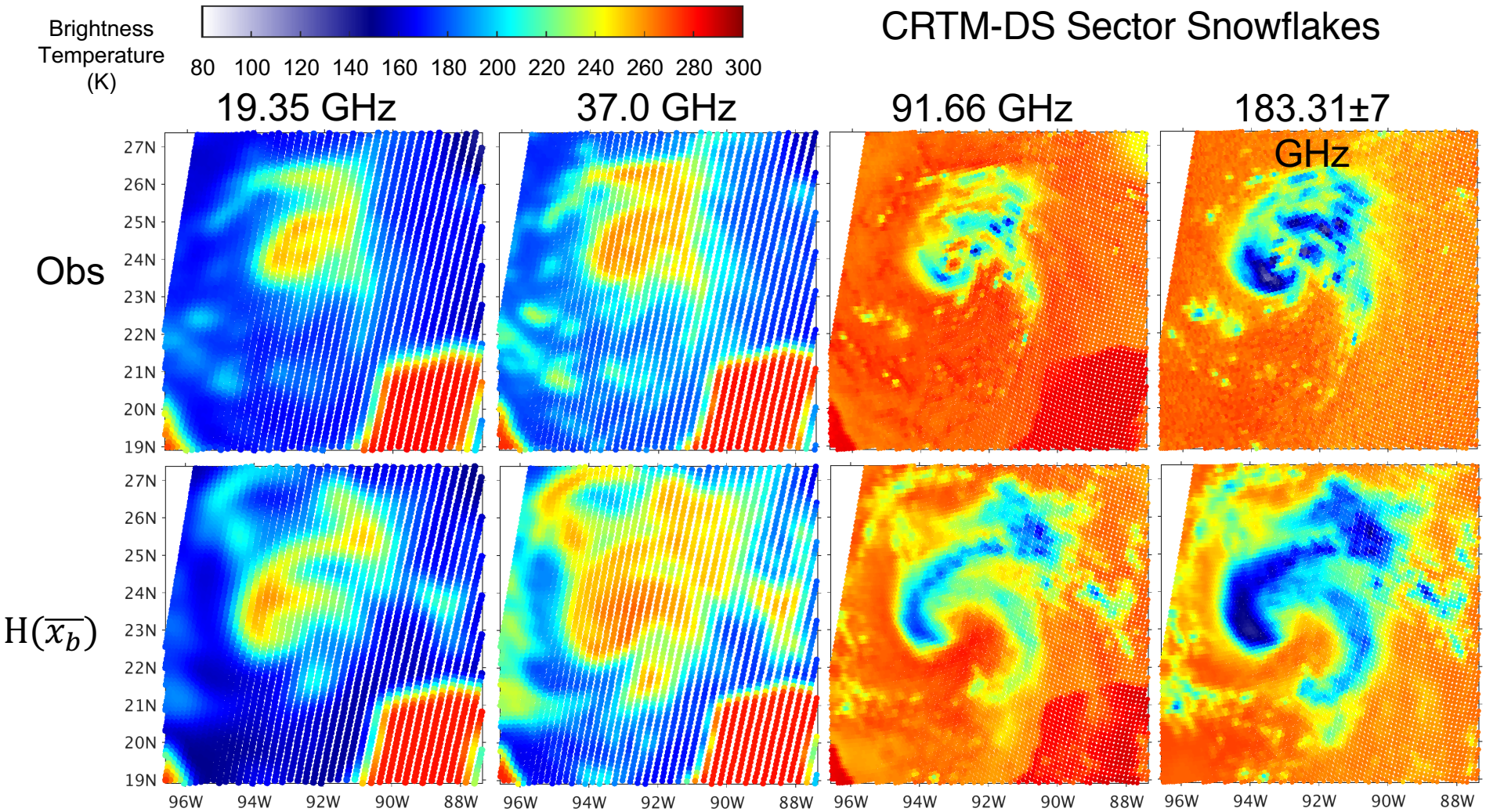
Assimilating All-sky Satellite Radiances: Harvey (2017)

Independent Observations vs. EnKF analysis



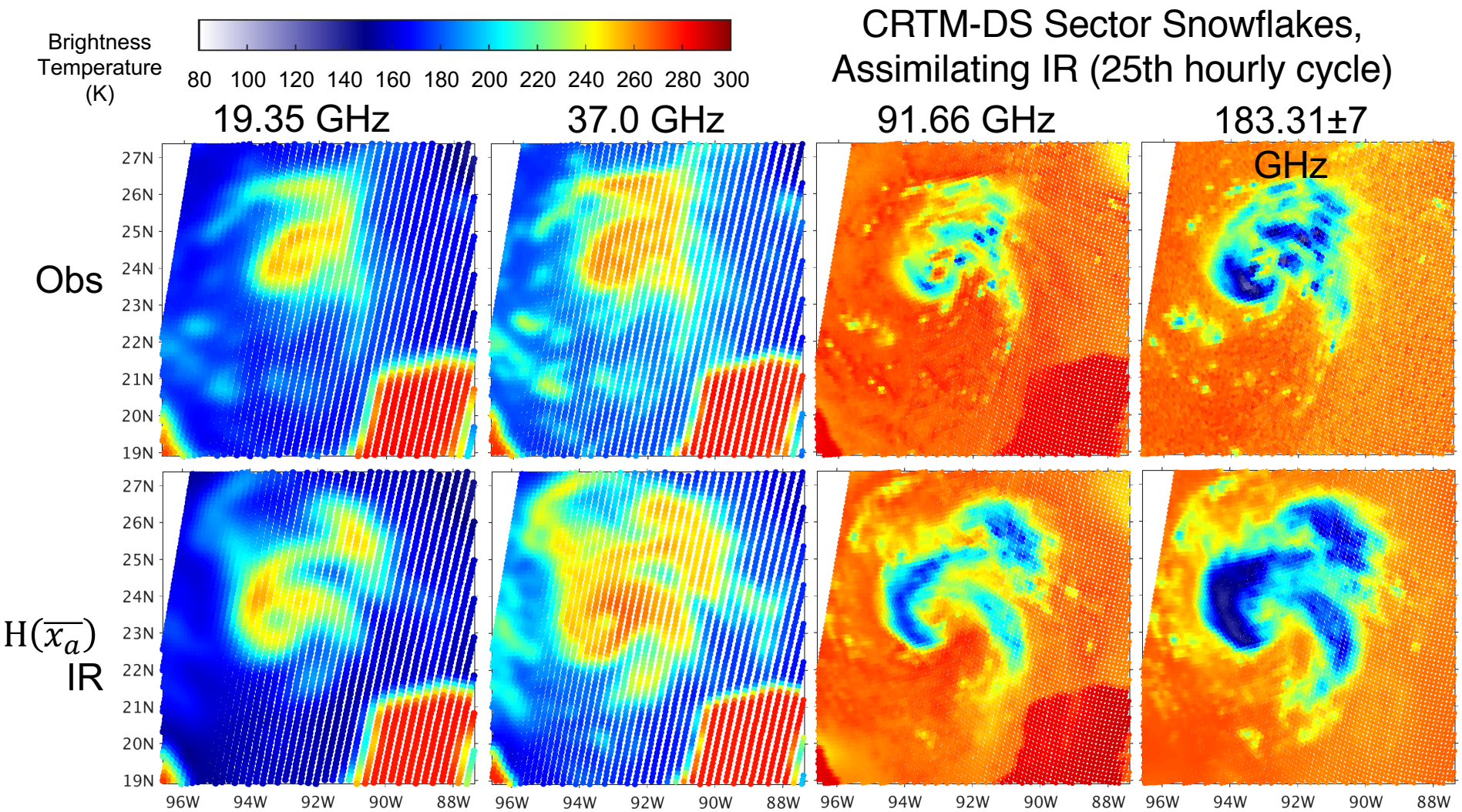
Assimilating All-sky Satellite Radiances: Harvey (2017)

WRF/CRTM simulated SSMIS MW radiance after 24-h IR EnKF



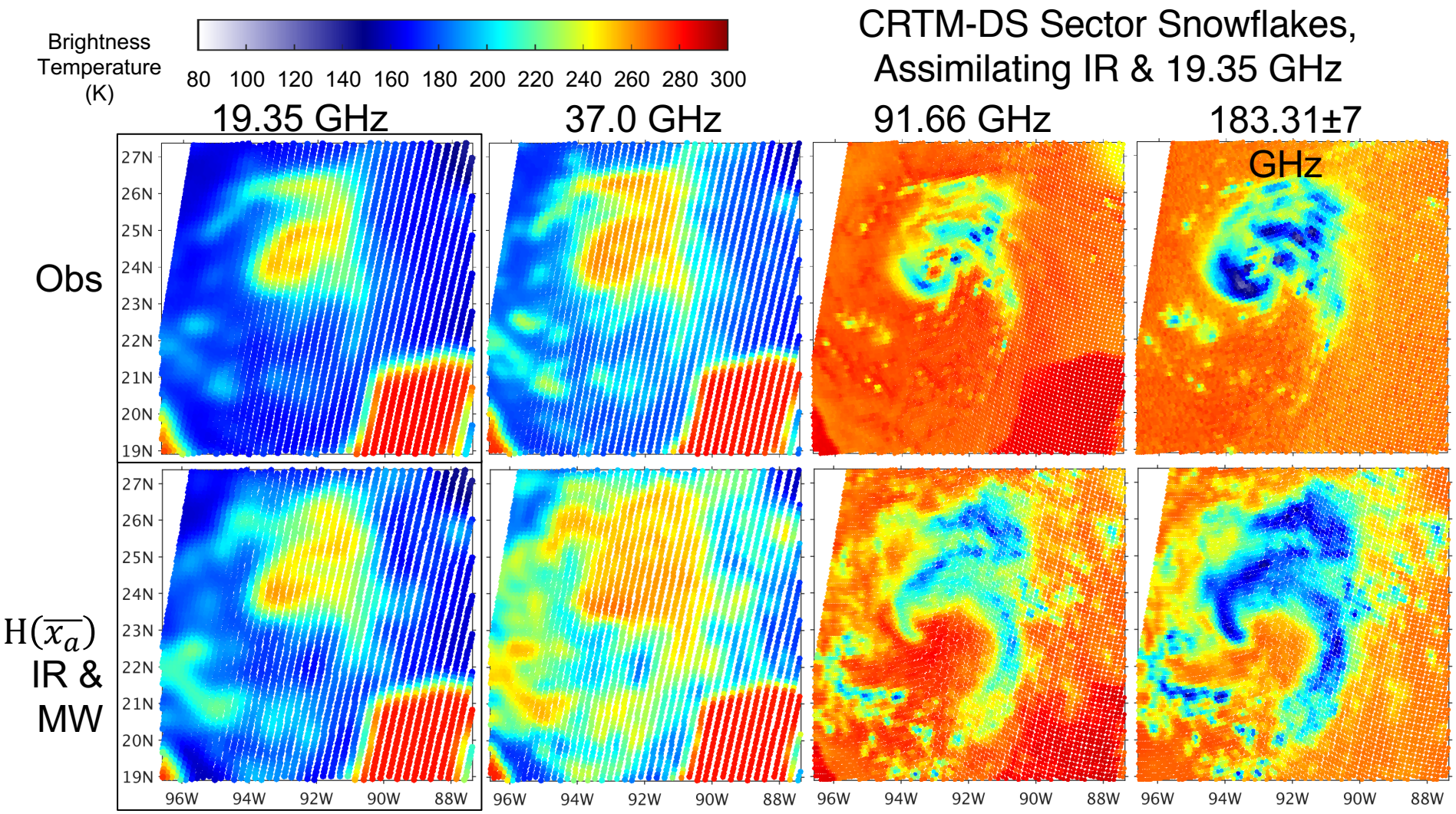
Assimilating All-sky Satellite Radiances: Harvey (2017)

WRF/CRTM simulated SSMIS MW radiance with new IR EnKF



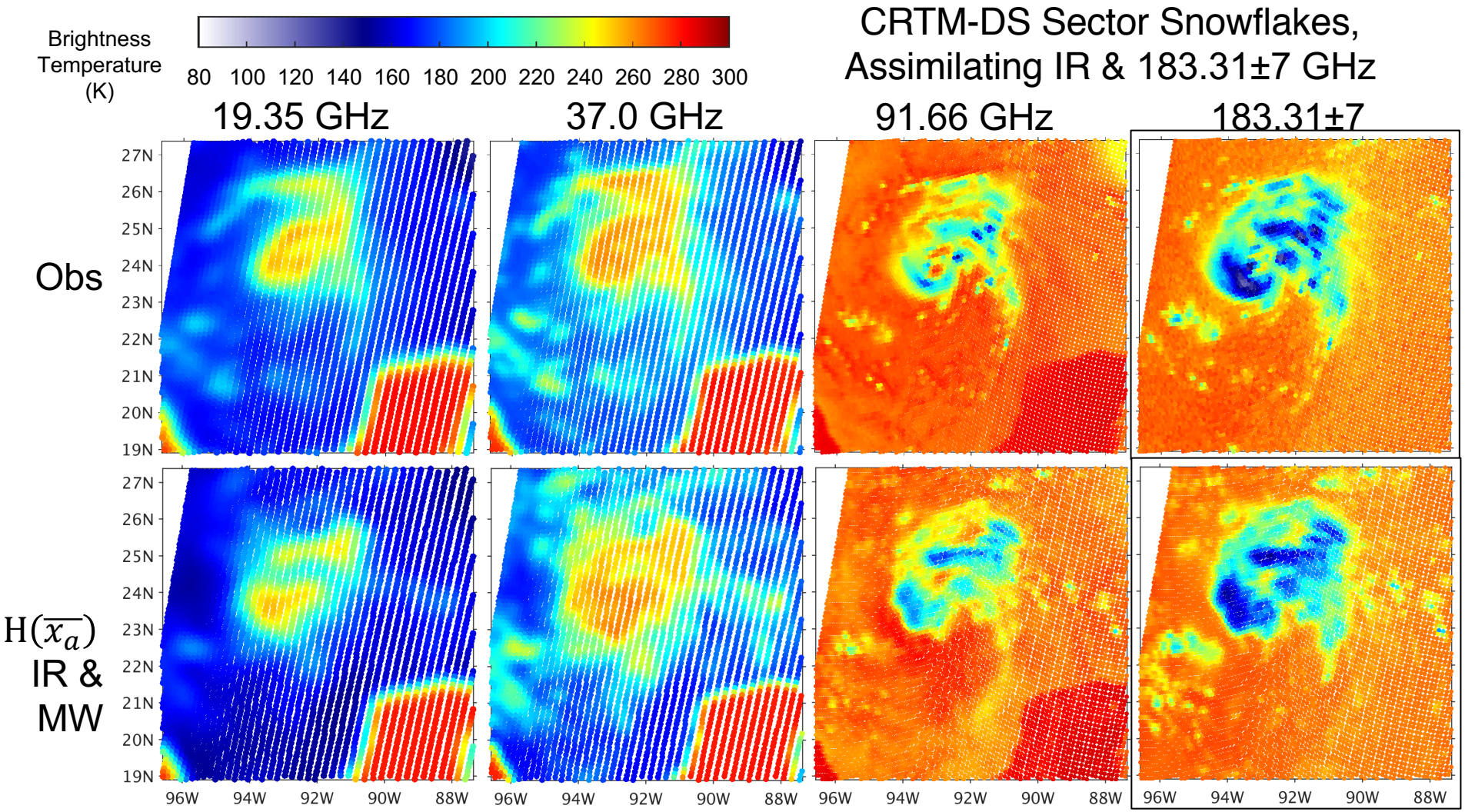
Assimilating All-sky Satellite Radiances: Harvey (2017)

WRF/CRTM simulated SSMIS MW radiance with IR/MW EnKF



Assimilating All-sky Satellite Radiances: Harvey (2017)

WRF/CRTM simulated SSMIS MW radiance with IR/MW EnKF

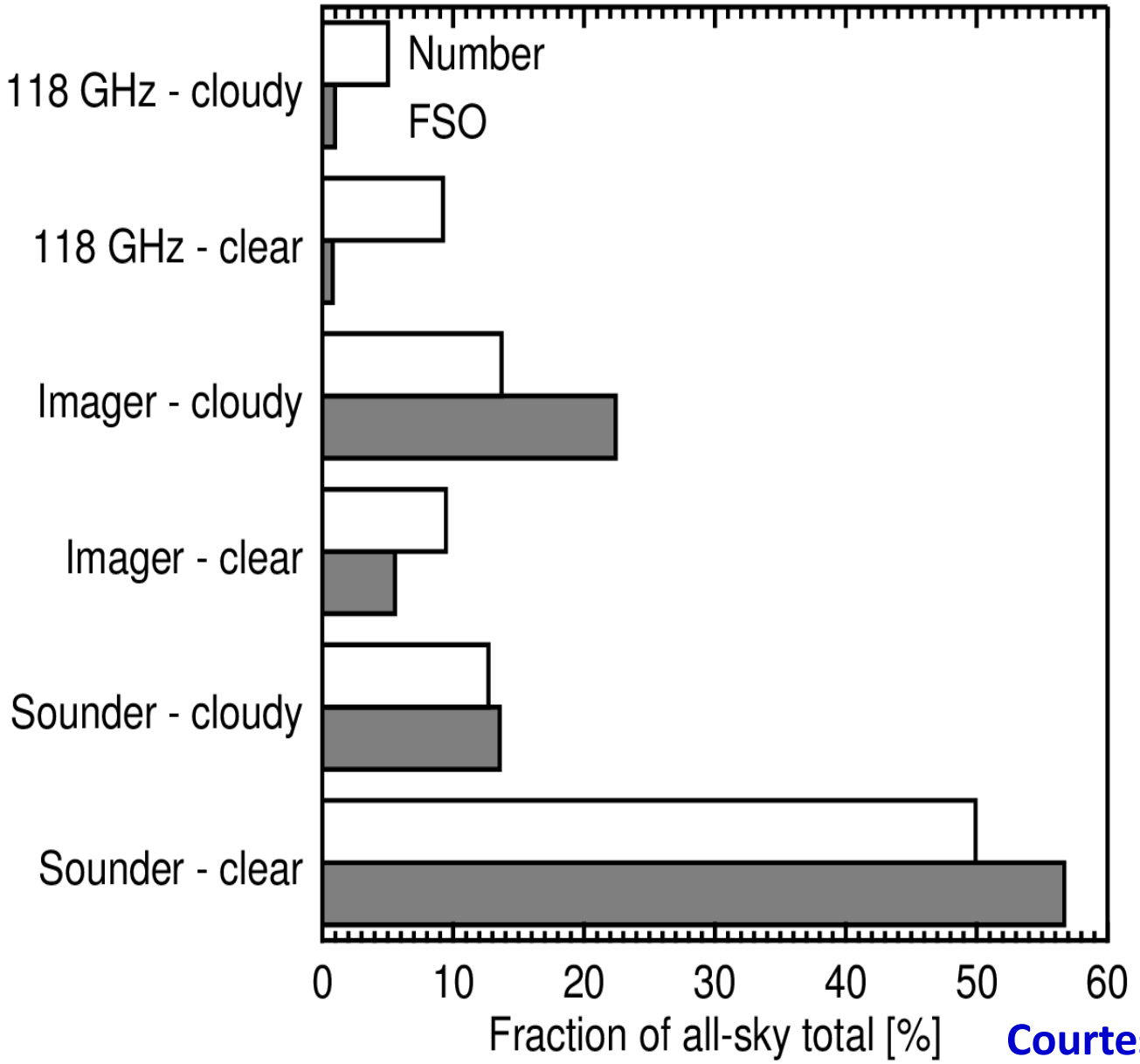


Concluding Remarks

- Convection-permitting EnKF assimilation of GOES-R all-sky radiance show great success for hurricane analysis & prediction
- Assimilation of cloudy microwave radiances is also promising but more challenging with key issues such as:
  - how to maintain consistency between model microphysics, CRTM and the wild nature of hydrometer distribution and shape
  - how to have microphysics distribution-specific radiative transfer for nonspherical particles given soft-sphere model microphysics
- Time is now to holistically integrate all-sky IR/MW radiances with convection-permitting models for better NWP prediction and global precipitation estimation via advanced data assimilation

State-of-the-Science: Importance of Cloudy and Precipitating Scenes

FSO of satellite radiances, August 2016 **(100% = 9 all-sky satellite radiance measurements)**



Imagers: Cloudy and precipitating scenes give more FSO than clear-sky scenes

Sounders: Cloudy and precipitating scenes have same per-obs FSO as clear-sky scenes

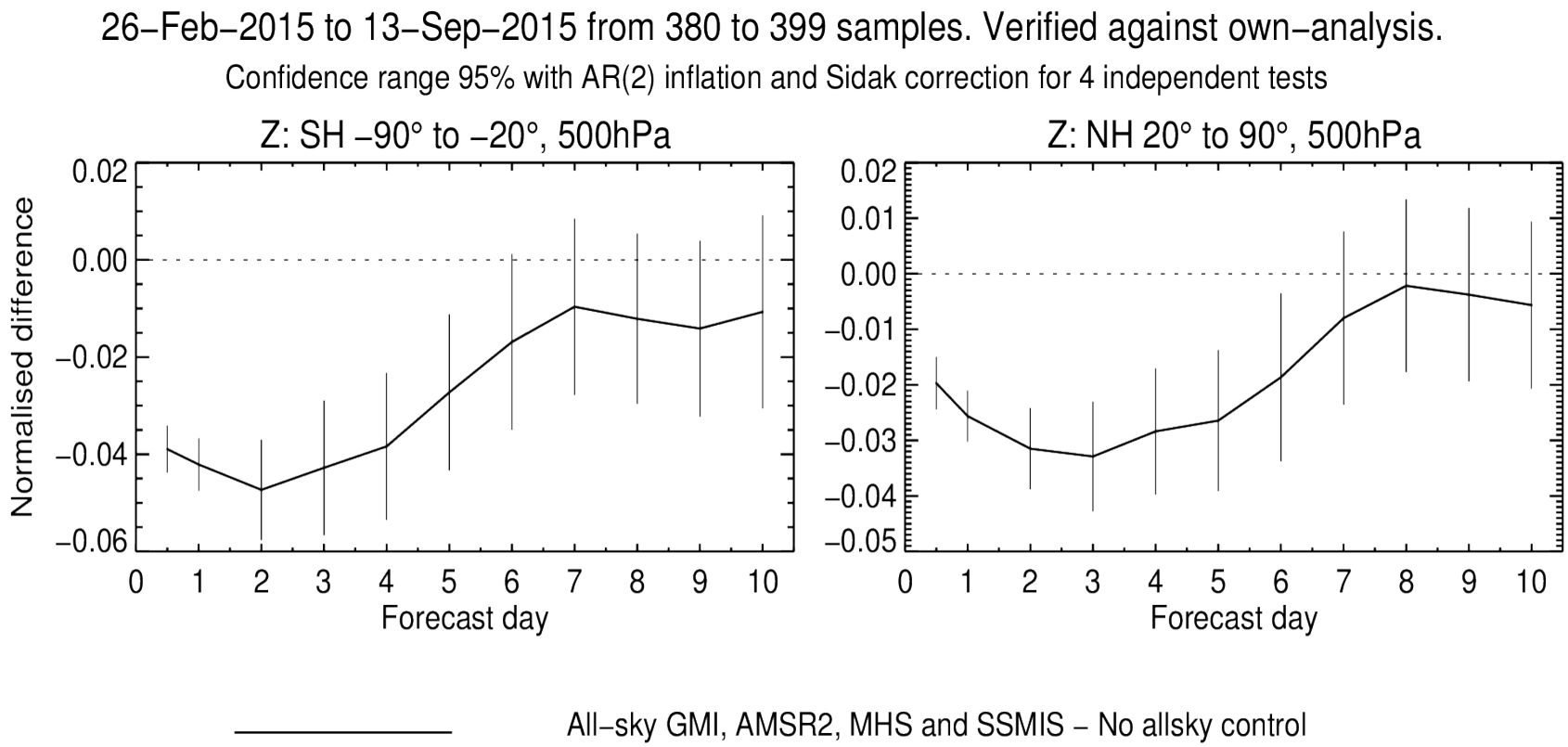
But don't forget all-sky gives a more optimal assimilation of "clear" scenes (going to all-sky at least doubled the forecast impact of MHS)

Courtesy of Alan Geer at ECMWF

State-of-the-Science: Importance of Cloudy and Precipitating Scenes

High FSO => real improvements in medium-range synoptic forecasts

Mechanism: *4D-Var can infer dynamical initial conditions from observed WV, cloud and precipitation*



ECMWF

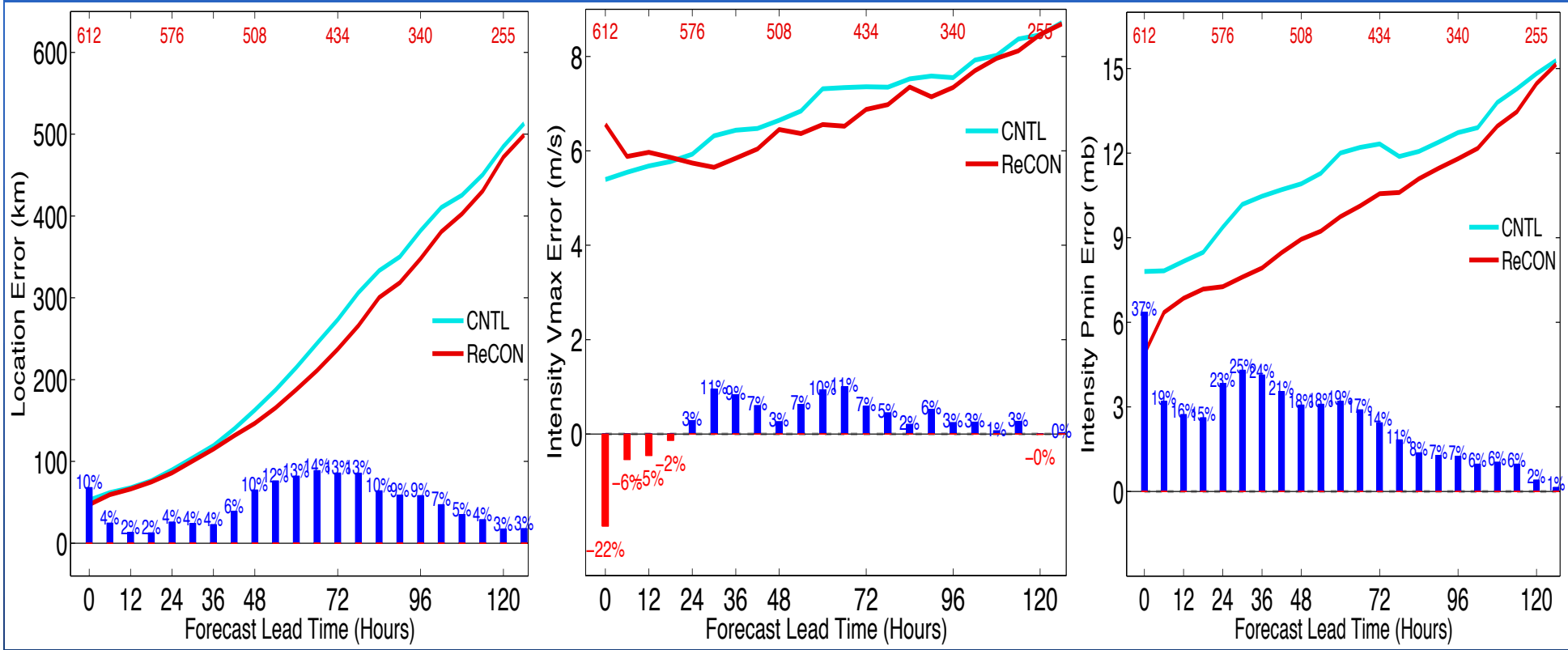
Courtesy of Alan Geer at ECMWF

WRF-EnKF Performance w/ versus w/o Aircraft OBS

for HFIP/NHC selected RDITT cases w/o TDR during 2008-2012

WRF-EnKF: 3 domains (27, 9 , 3km), 60-member ensemble, PSU TC flux scheme

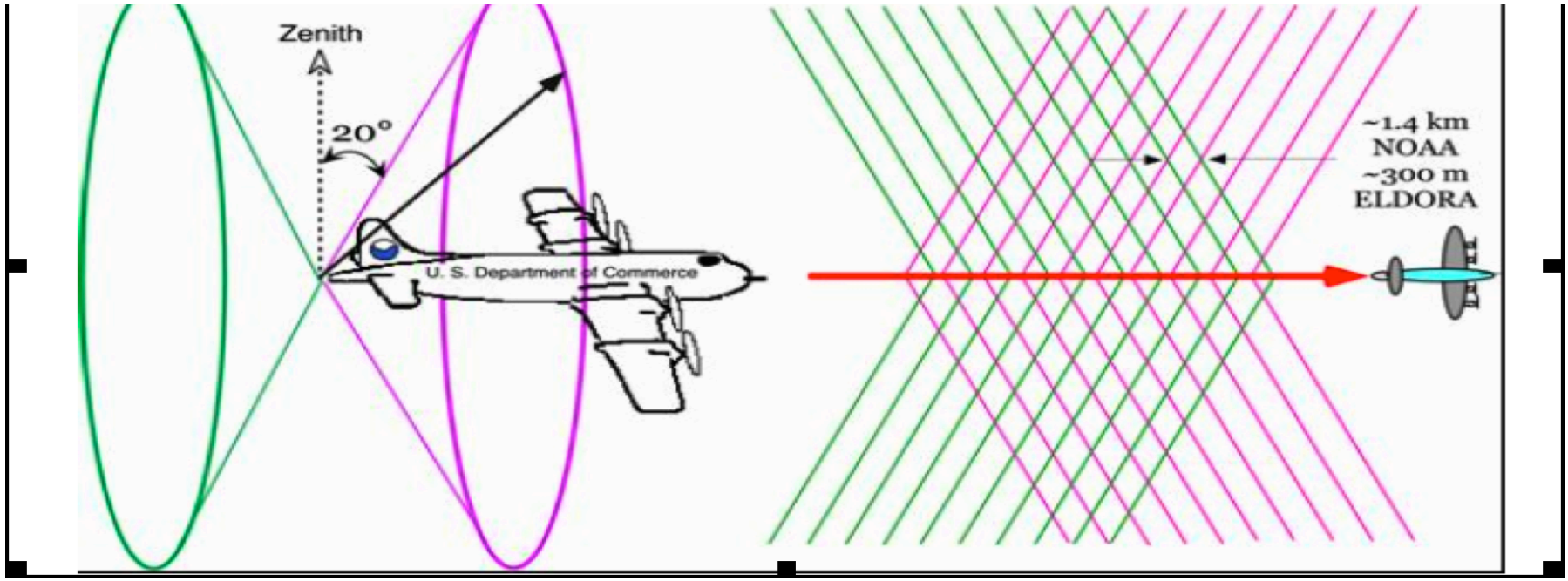
Position error (km) **Vmax error (knots)** **Pmin error (mb)**



(Weng and Zhang, 2016 JMSJ)

Assimilate Airborne Doppler Winds with WRF-EnKF

Available for 20+ years but never used in operational models due to the lack of resolution and/or the lack of efficient data assimilation methods



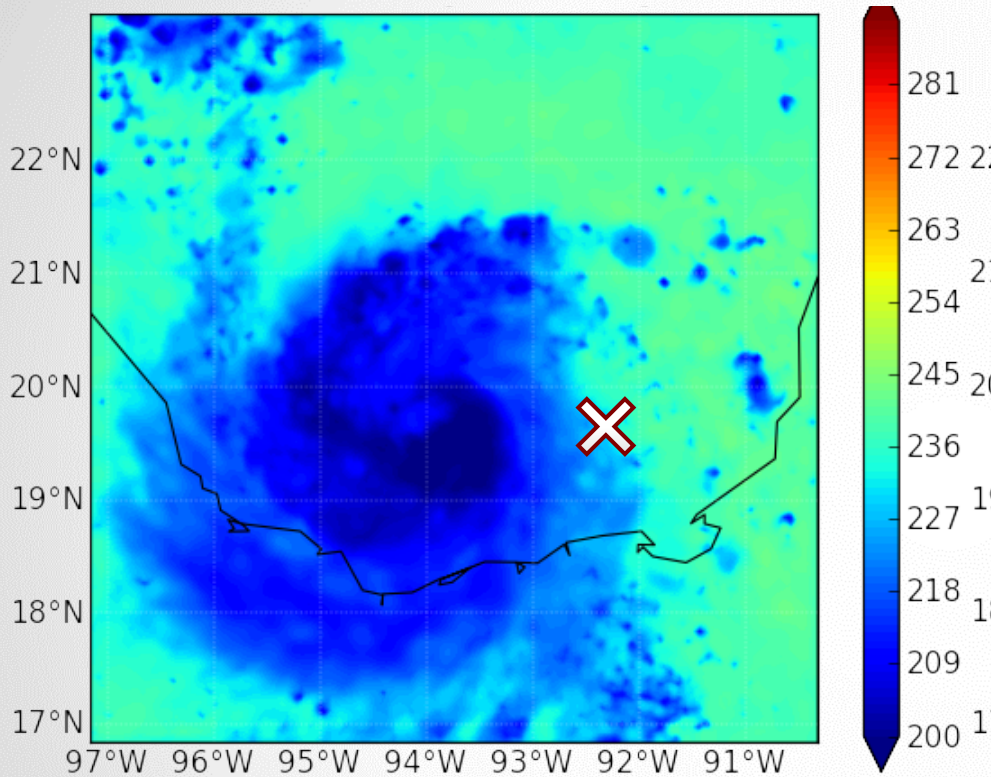
Superobservations: 1. Separate forward and backward scans; 2. treat every 3 adjacent full scans as one fixed-space radar (translation<5km); 3. thinning ---one bin for 2 km in radial distance and 3 degree in scanning angle; 4. use medium as SO after additional QC checking

(Weng and Zhang 2012 MWR)

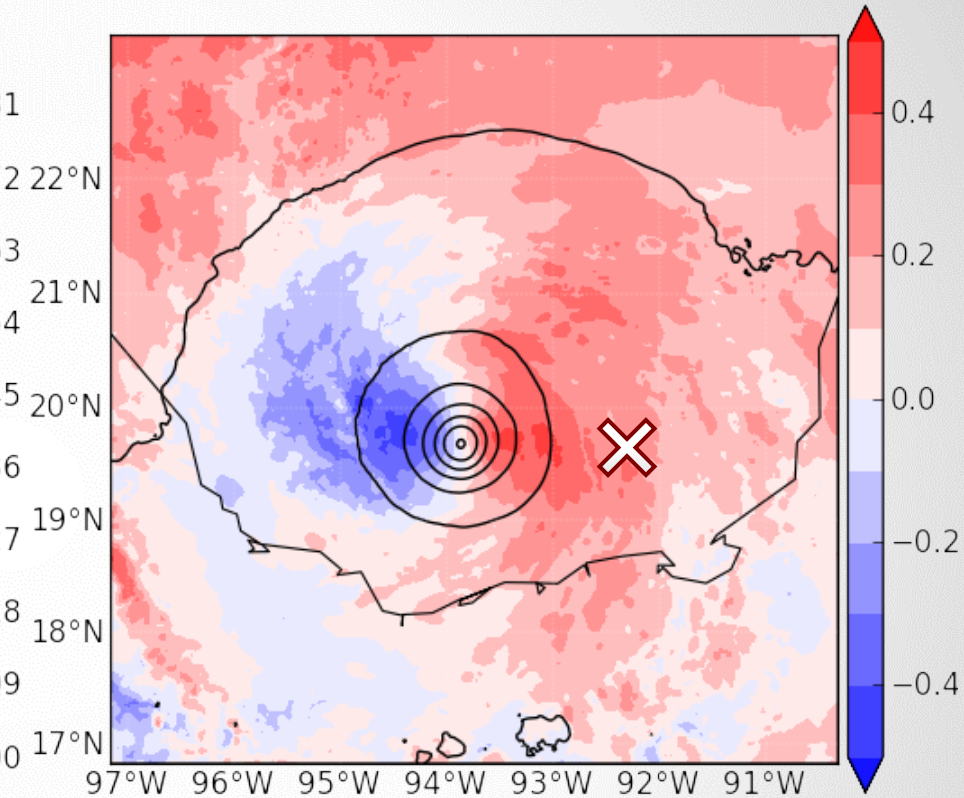
These SOs are generated on flight of NOAA P3's; transmitted to ground in real-time; adopted and assimilated operationally by NCEP/HWRF in 2013

EnKF Assimilation of All-sky Radiance from GOES-R

Simulated Radiance and Correlations to SLP for a TC



Simulated GOES-R ABI Ch8 (6.19 μm) radiance

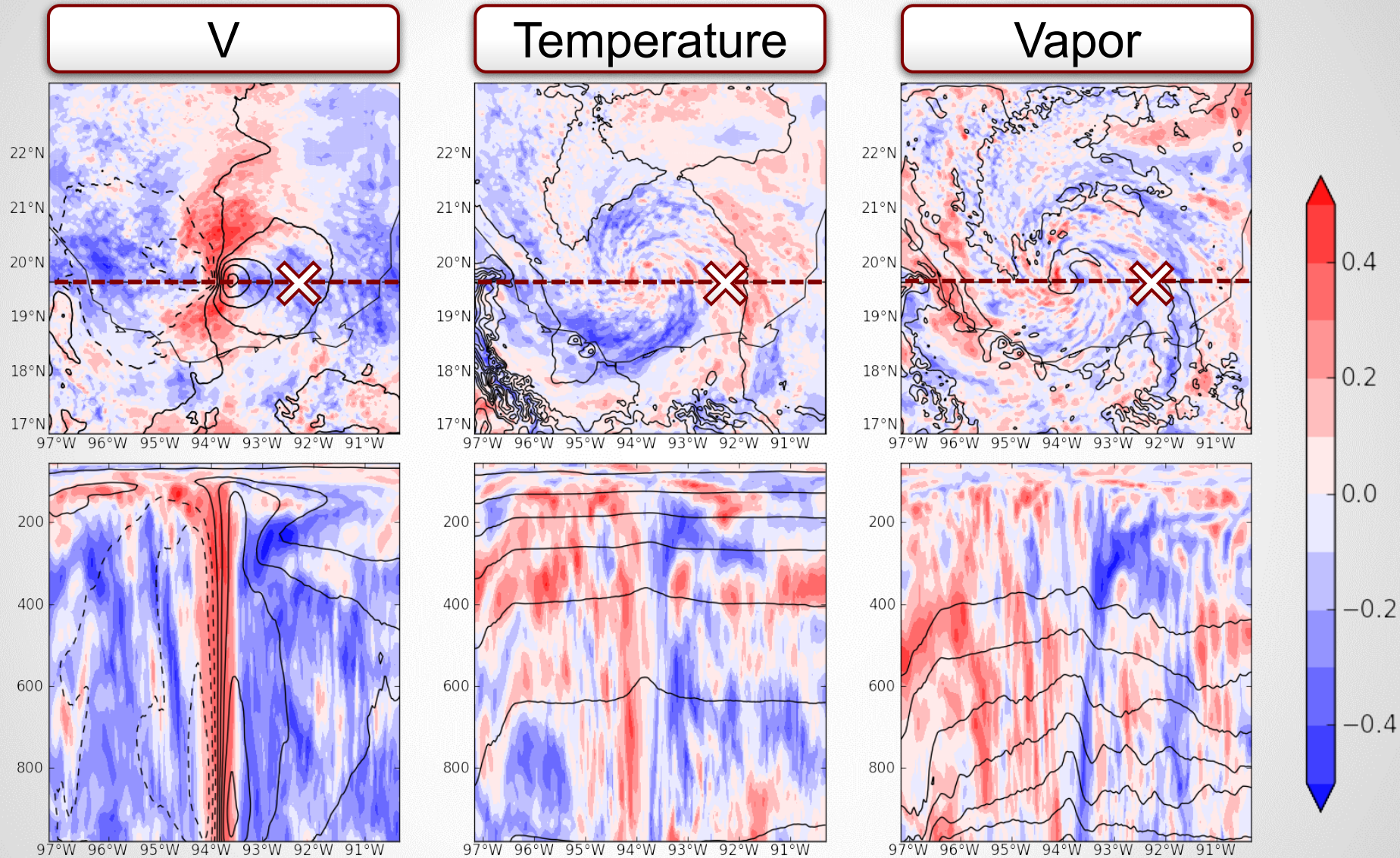


Colors: ensemble correlation of SLP to radiance at 'X'

Contours: ensemble mean SLP

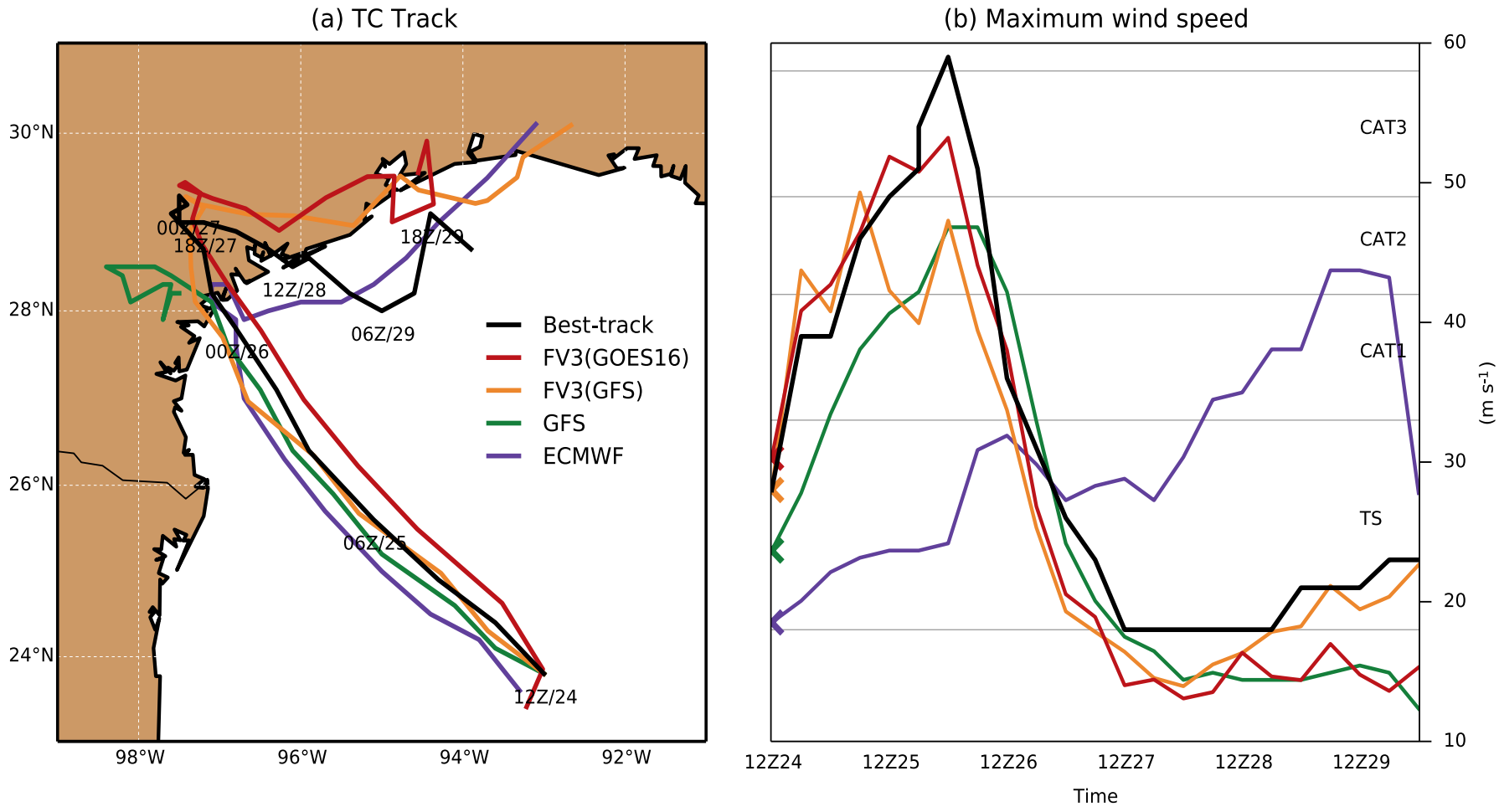
(Zhang, Minamide & Clothiaux, 2016 GRL)

Correlations of Radiance to Model State Variables



Colors: ensemble correlation to radiance (6.19 μm) at ‘x’ ,

Contours: ensemble mean at 930 hPa (top) & 19.6 N (below)


(a) TC Track
30°N
28°N
26°N
24°N
98°W
96°W
94°W
92°W
00Z/27
18Z/27
12Z/28
18Z/29
06Z/29
00Z/26
06Z/25
12Z/24
Best-track
FV3(GOES16)
FV3(GFS)
GFS
ECMWF
(b) Maximum wind speed
CAT3
CAT2
CAT1
TS
60
50
40
30
20
10
(m s-1)
12Z24
12Z25
12Z26
12Z27
12Z28
12Z29
Time

REVIEW

Review of the Ensemble Kalman Filter for Atmospheric Data Assimilation

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(Manuscript received 17 December 2015, in final form 6 June 2016)

ABSTRACT

This paper reviews the development of the ensemble Kalman filter (EnKF) for atmospheric data assimilation. Particular attention is devoted to recent advances and current challenges. The distinguishing properties of three well-established variations of the EnKF algorithm are first discussed. Given the limited size of the ensemble and the unavoidable existence of errors whose origin is unknown (i.e., system error), various approaches to localizing the impact of observations and to accounting for these errors have been proposed. However, challenges remain; for example, with regard to localization of multiscale phenomena (both in time and space). For the EnKF in general, but higher-resolution applications in particular, it is desirable to use a short assimilation window. This motivates a focus on approaches for maintaining balance during the EnKF update. Also discussed are limited-area EnKF systems, in particular with regard to the assimilation of radar data and applications to tracking severe storms and tropical cyclones. It seems that relatively less attention has been paid to optimizing EnKF assimilation of satellite radiance observations, the growing volume of which has been instrumental in improving global weather predictions. There is also a tendency at various centers to investigate and implement hybrid systems that take advantage of both the ensemble and the variational data assimilation approaches; this poses additional challenges and it is not clear how it will evolve. It is concluded that, despite more than 10 years of operational experience, there are still many unresolved issues that could benefit from further research.

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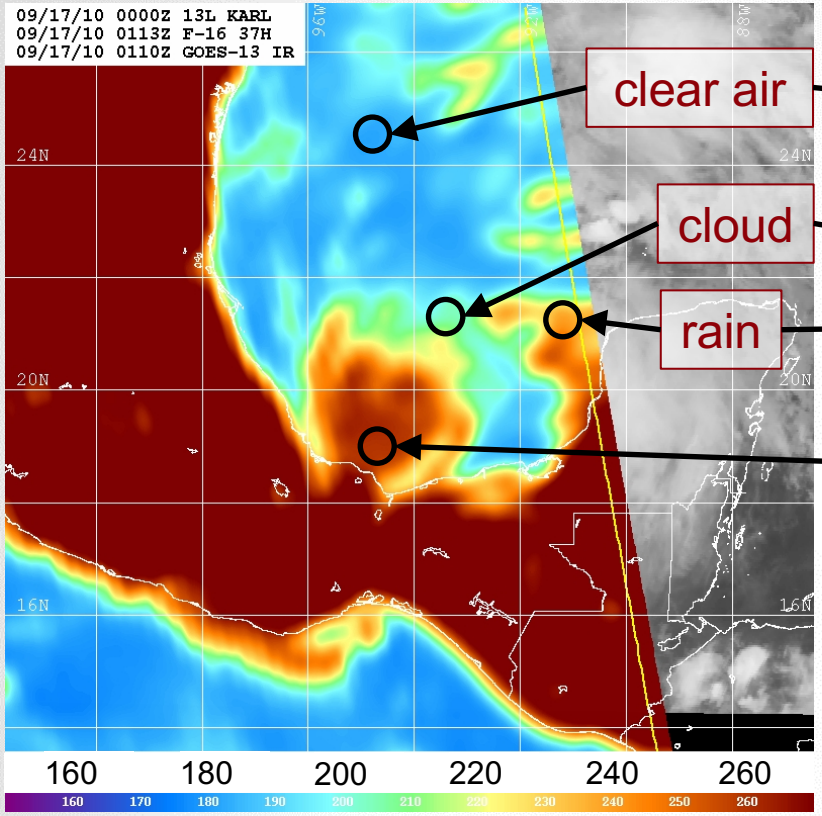
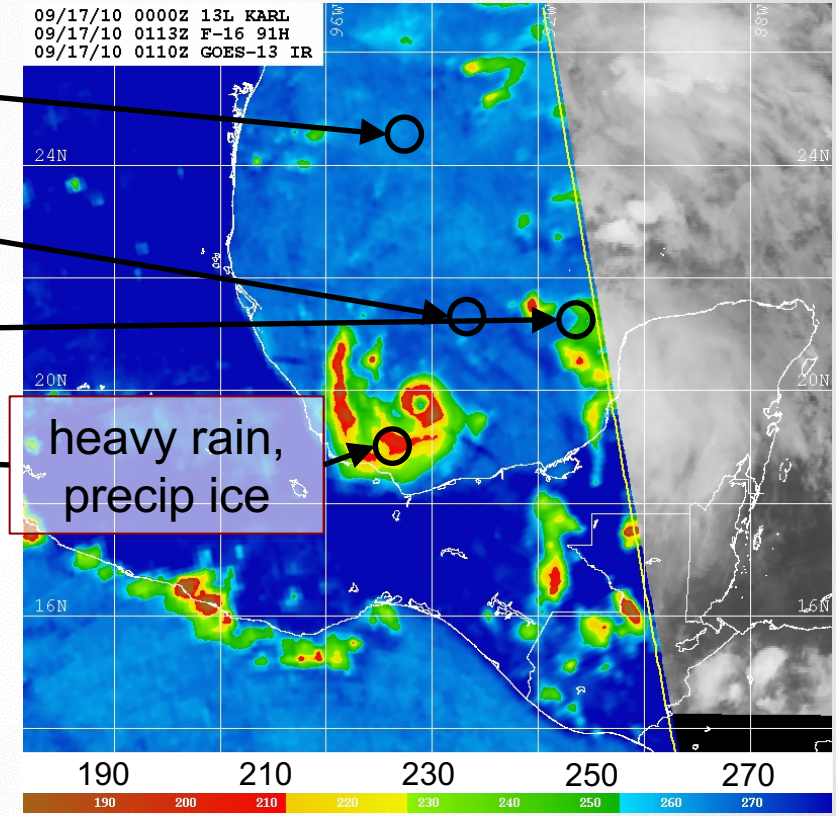
Microwave Radiometers and Precipitation

Low-mid microwave freq. (37 GHz)



High-mid microwave freq. (91.7 GHz)



Hurricane Karl 09/17/10 0113Z
(SSMI/S image courtesy NRL)

- Rain and cloud liquid net add to low emission by water
- Some scattering by precipitation ice
- Scattering by precipitation ice dominates the signal

On going work with Scott Sieron and Eugene Clothiaux

Data assimilation used in operational global models

ECWMF: adjoint-based as an ensemble of 4DVar but with hybrid covariance

UK-Met: adjoint-based E4DVar in operation, better than ensemble-based 4DEnVar

NCEP: ensemble-based 4DEnVar

CMC: 4DEnVar for deterministic forecasts, EnKF for ensemble prediction

PSU WRF-based multi-functional regional-scale ensemble and hybrid data assimilation system

PSU **WRF-EnKF** (Zhang et al. 2009a; Weng & Zhang 2012): publically released

NCAR WRFDA-**3DVar** (Huang et al. 2009): publically released

NCAR WRFDA-**4DVar** (X Zhang et al. 2014): publically released

E3DVar/3DenVar (hybrid/coupling of EnKF & 3DVar) (Zhang et al. 2013)

E4DVar (coupling of EnKF & 4DVar) (Zhang et al. 2009b; Poterjoy & Zhang 2014)

4DEnVar (ensemble-based 4D hybrid) (Liu et al. 2008; Poterjoy & Zhang 2015)

Extensive review on ensemble assimilation for NWP in Houtekamer and Zhang (2016)

Mesoscale NWP Microphysics

- Most bulk species are assumed either monodisperse, or having a generalized gamma particle size distribution (PSD):

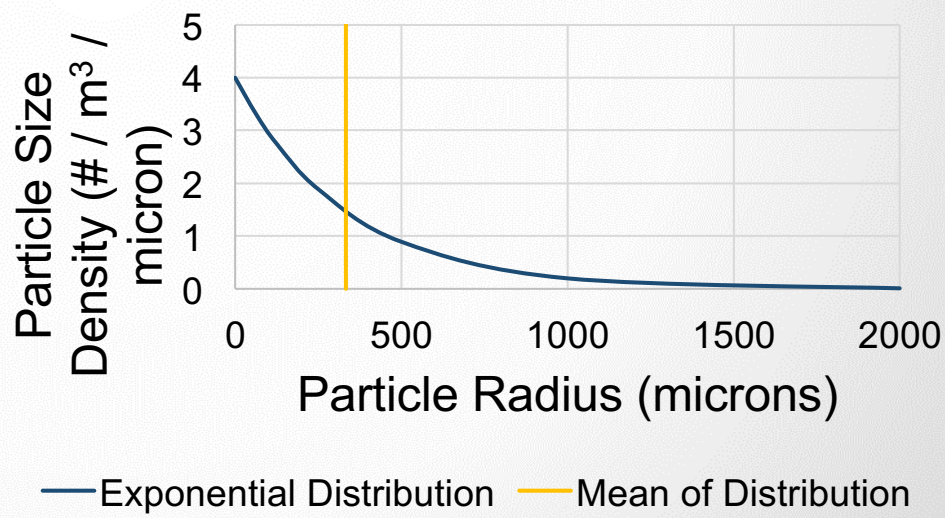
$$N(r) = N_0 r^{\mu} \exp(-\lambda r),$$

  - Common is Marshall-Palmer distribution: $\mu = 0$

- Most frozen species assumed to be homogeneous "soft spheres"
  - Mie theory well-represents scattering and absorption

- Schemes differ by some PSD parameter values and particle properties

WSM6 graupel λ = 3000 m^{-1} (0.078 g m^{-3})



Current ECMWF model: cloud liquid, cloud ice, rain – Mie sphere; snow – Liu sector snowflake

Potential Issue with Default CRTM Using Effective Radius

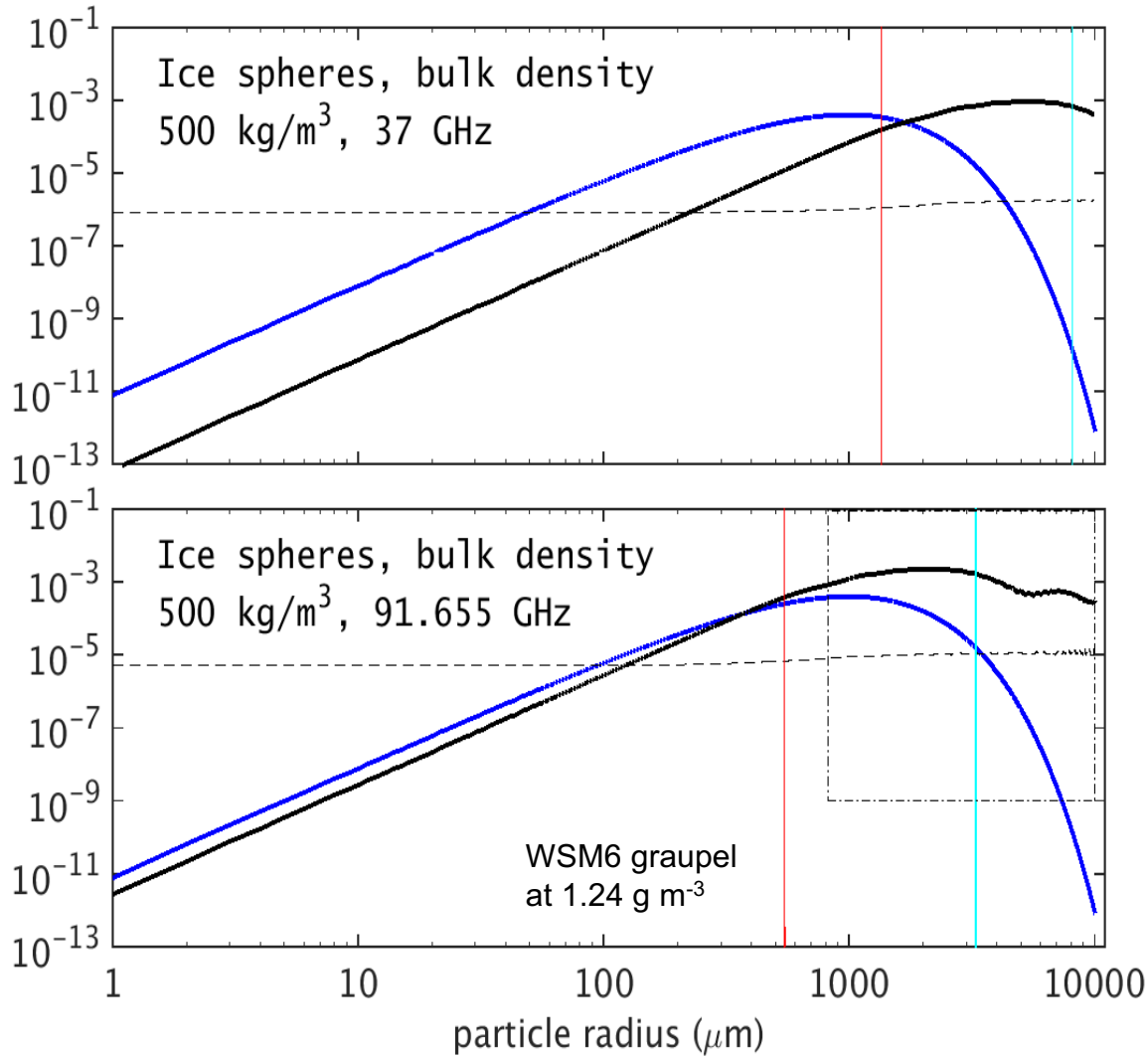
- The community defines effective radius as

$$r_{eff} = \frac{\int_{r2}^{r1} r^3 N(r) dr}{\int_{r2}^{r1} r^2 N(r) dr}$$

  - This is "mean radius for scattering" for <u>scattering by a particle $\propto r^2$</u> (Hansen and Travis 1974)

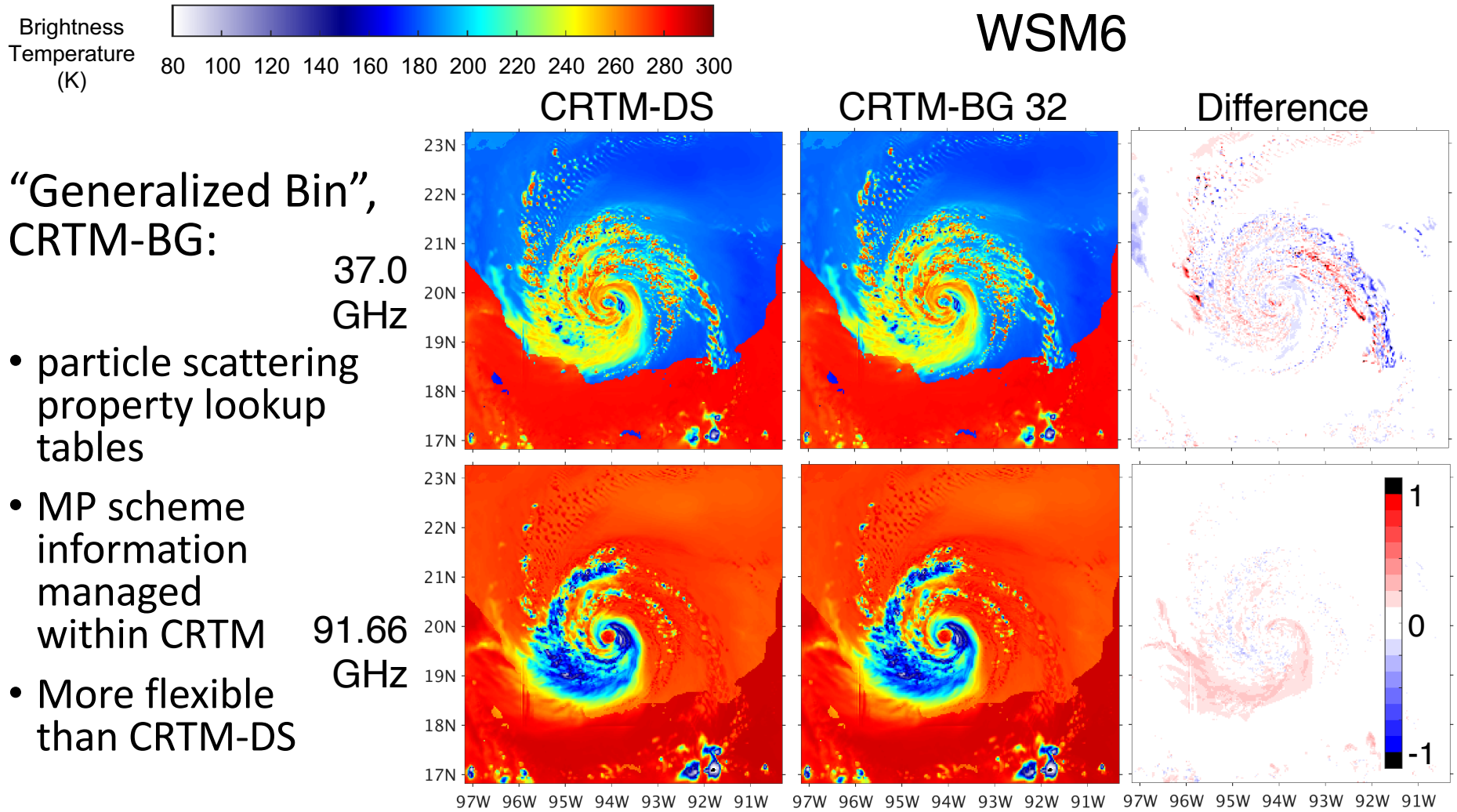
- For precipitation in microwave, scattering by particles is NOT $\propto r^2$
  - <u>Scattering $\propto r^6$</u> for particles much smaller than wavelength
  - Large fraction of mass in particle sizes ~wavelength

- Effective radius fails



Black: scattering coeff. (m^2 kg^{-1})
Dashed: absorption coeff. (m^2 kg^{-1})
Blue: sample particle mass distribution (kg m^{-3} μm^{-1}) of graupel-like ice spheres

WSM6

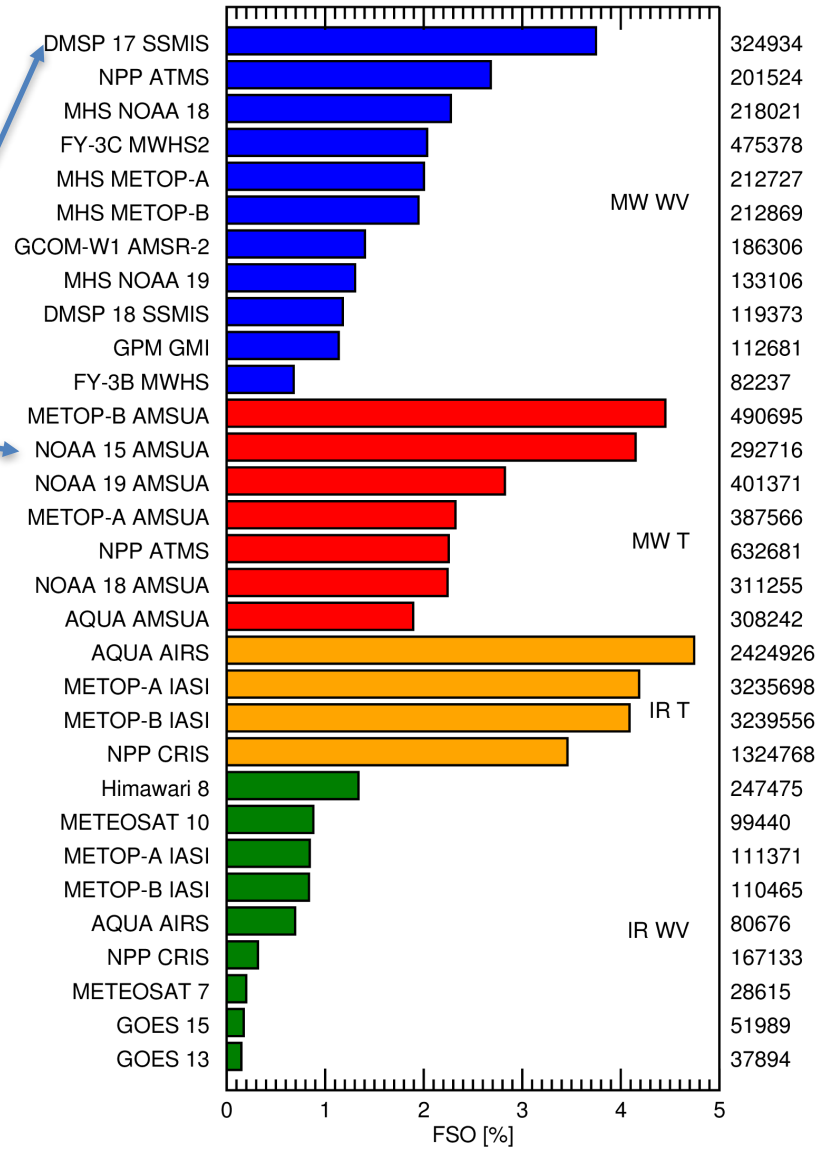


"Generalized Bin", CRTM-BG:

- particle scattering property lookup tables
- MP scheme information managed within CRTM
- More flexible than CRTM-DS

State-of-the-Science: Importance of All-sky Radiances from ECMWF Operations

FSO of satellite radiances, August 2016 (100% = full operational observing system)



Microwave WV 20.4%

Microwave T 20.1%

Infrared T 16.5%

Infrared WV 5.4%

An SSMIS (combining imaging and humidity sounding channels) is nearly equivalent to the best of the temperature-sounding AMSU-As

Amount of information coming from humidity/cloud/precipitation is equivalent to what's coming from T sounding

There is great potential to get more from the infrared water vapour channels by going to all-sky

ECMWF

Courtesy of Alan Geer at ECMWF