Assimilation of all-sky infrared radiance from geostationary satellites

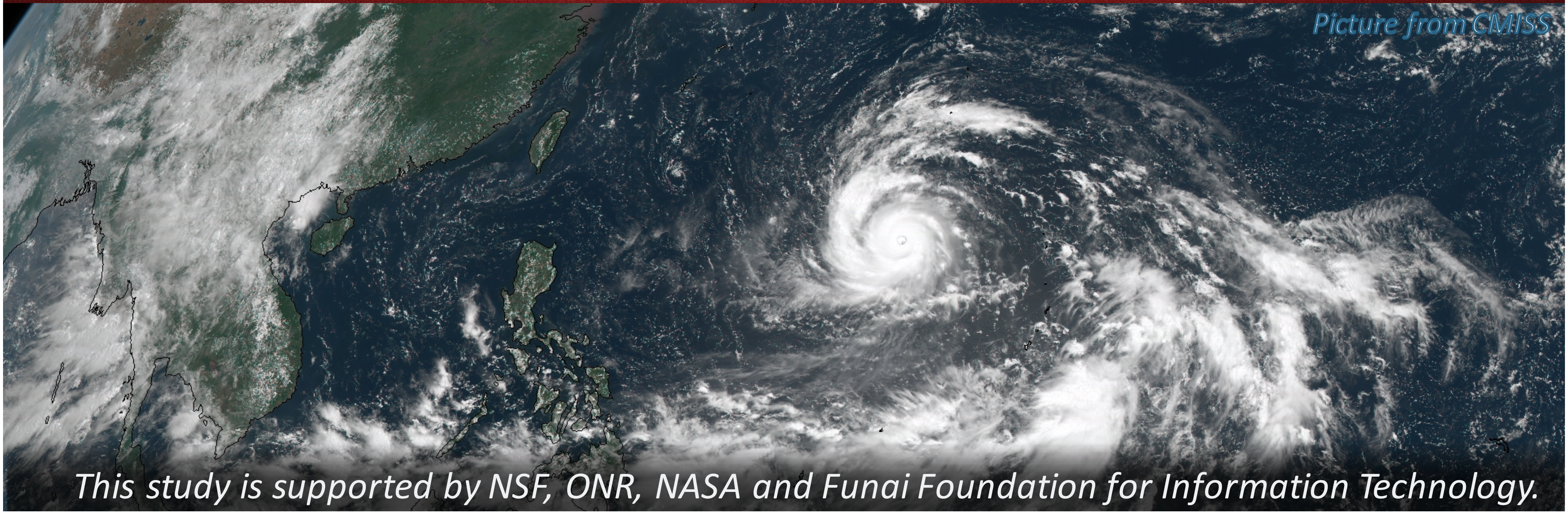
Masashi Minamide

Fuqing Zhang and Eugene Clothiaux

Department of Meteorology and

Center for Advanced Data Assimilation and Predictability Techniques (ADAPT),

The Pennsylvania State University



Picture from CMISS

This study is supported by NSF, ONR, NASA and Funai Foundation for Information Technology.

New Satellites! Himawari-8 AHI & GOES-R ABI

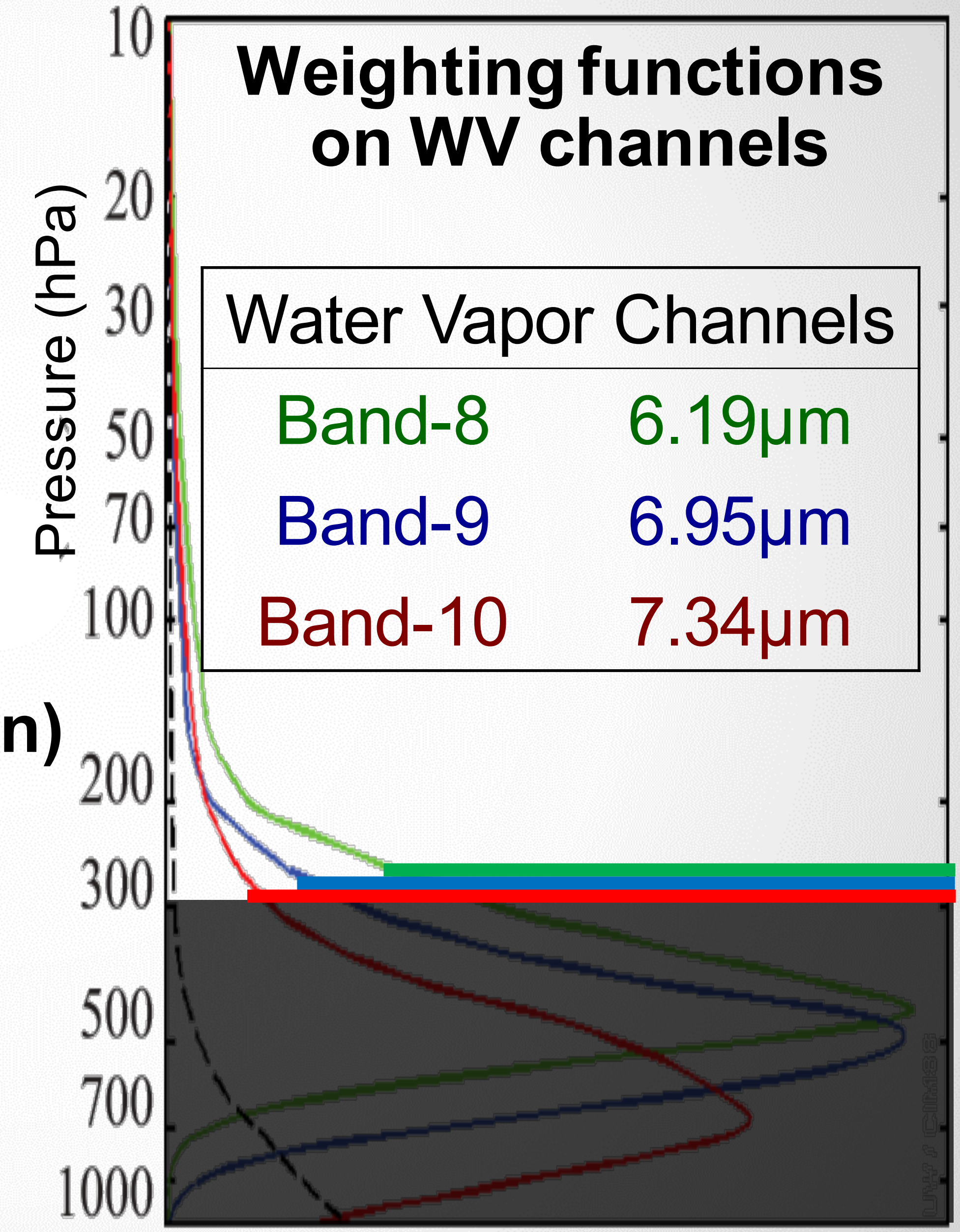
Launch Dates:

- **Oct 2014 (Himawari-8, Japan)**
- **Oct 2016 (GOES-R, USA)**

Coverage: **Hemispheric**

Frequency: **10-15 minutes**

Resolution: **2 km**



(*Otkin* 2012)

PSU WRF-EnKF via CRTM

t

WRF
(Skamarock et al. 2008)

t+dt

EnKF & CRTM
Zhang et al. (2009); Weng and Zhang (2012)

obs

$$X^a = X^b + K\left(y - \boxed{h(X^b)}\right)$$

$$BT = h(x^b)$$

Community Radiative Transfer Model
(**CRTM**; Han et al. 2006)

Ensemble-based data assimilation system

- Ensemble size: 60

Regional convective-permitting model

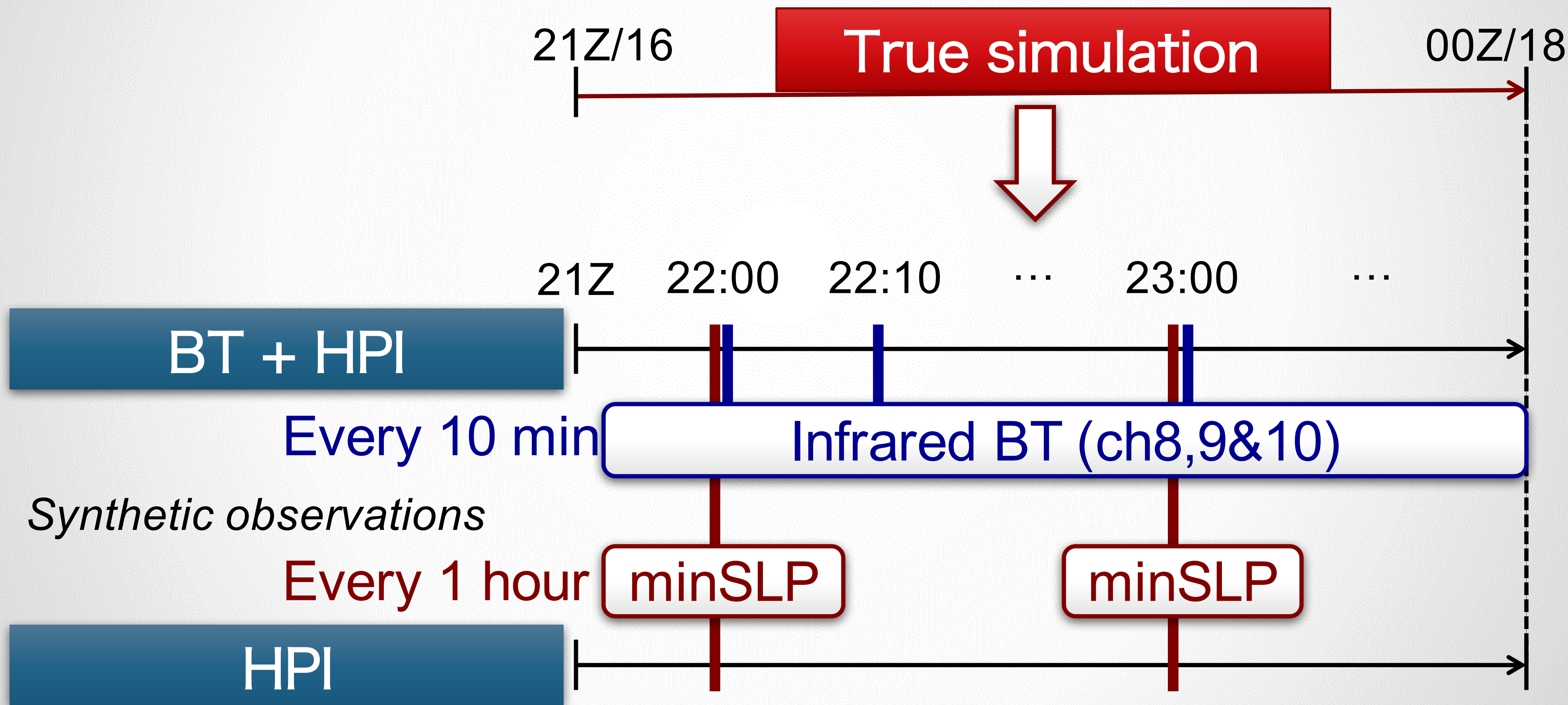
- Resolution: 27, 9 & 3 km (D1-D3)

Observation error modeling

- Adaptive Observation Error Inflation (Zhang, Minamide & Clothiaux, 2016, Minamide & Zhang, in prep)

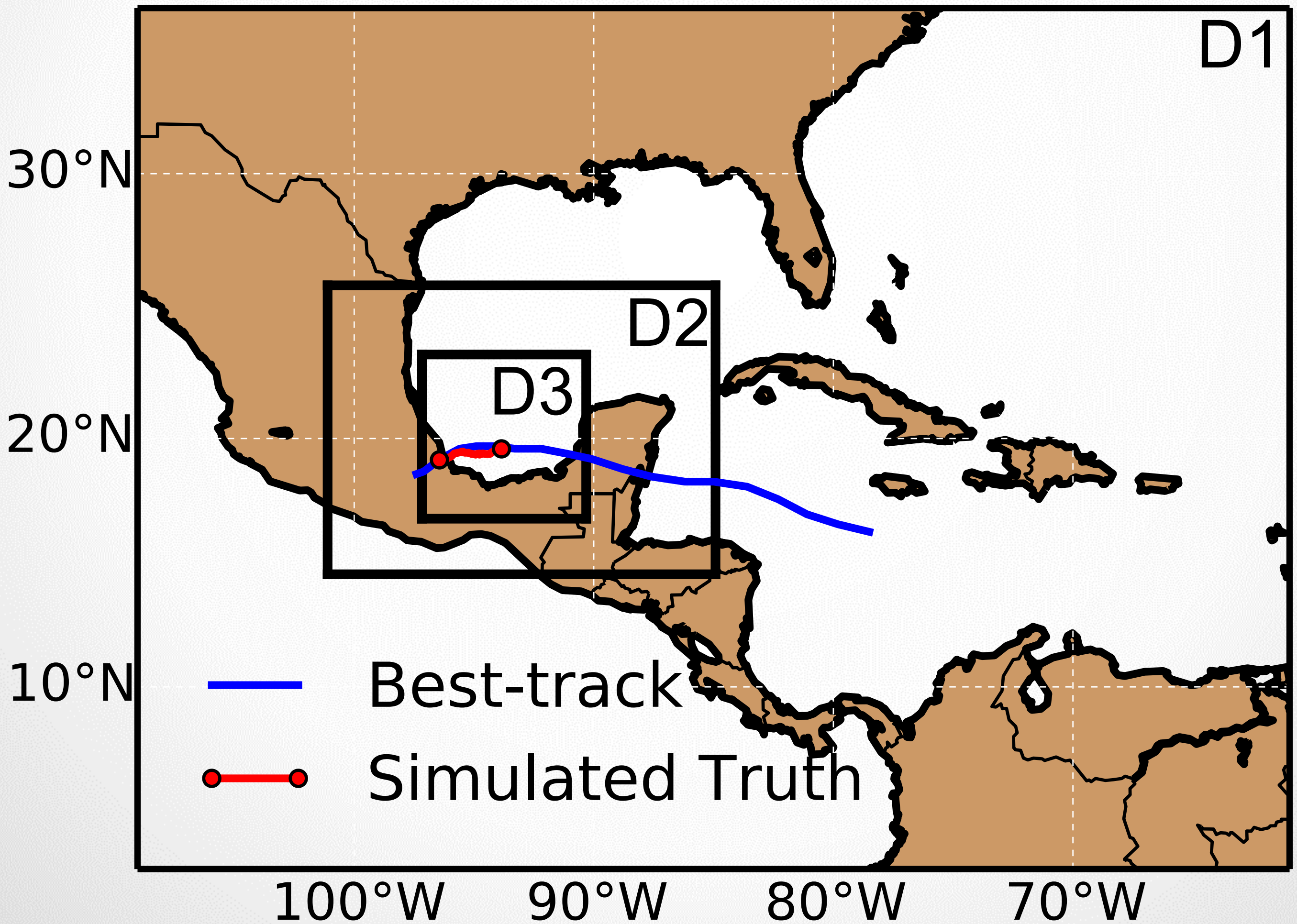
Observing System Simulation Experiments (OSSE)

Truth run: **Hurricane Karl**, 21Z 16 – 00Z 18 SEP 2010
Resolution: **27, 9 & 3 km (D1-D3), EnKF only for D3**



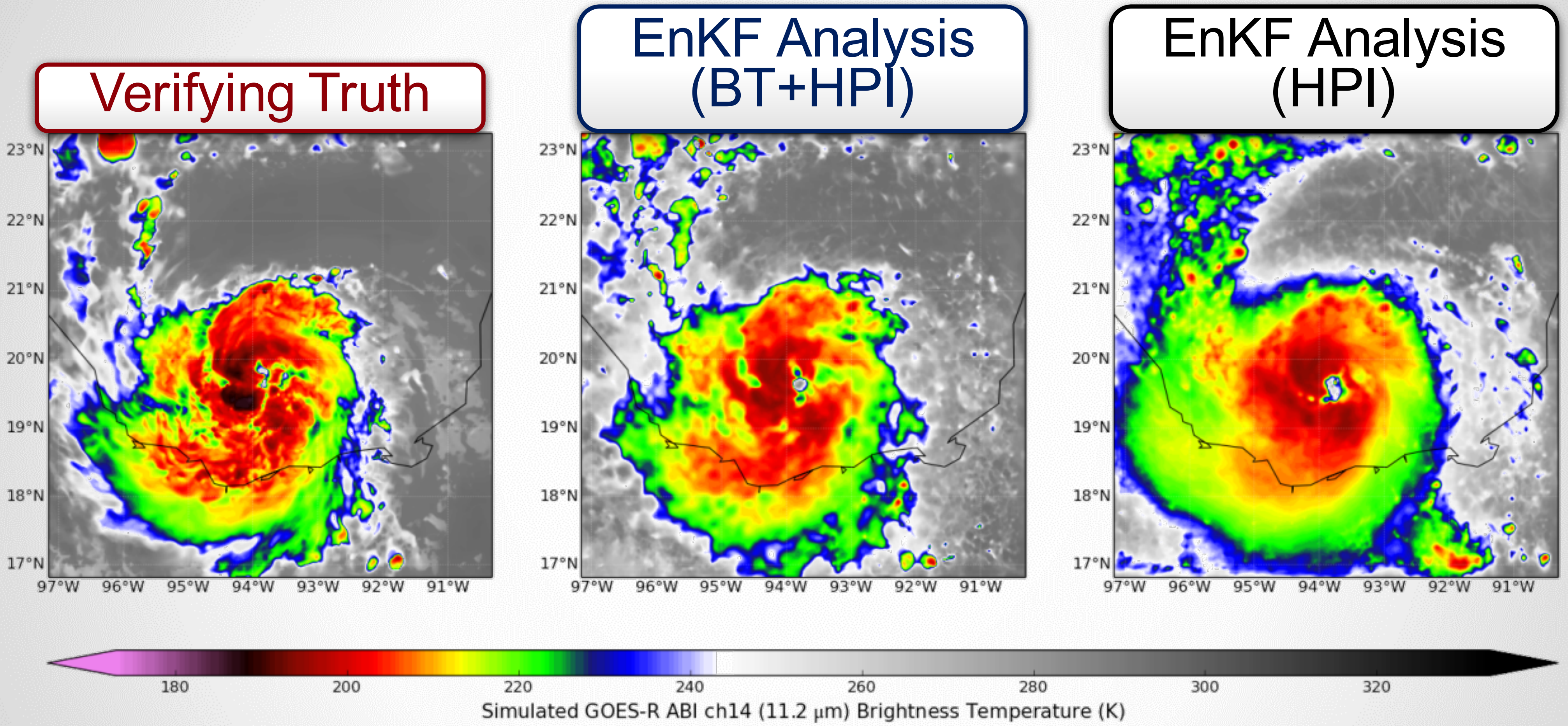
Observing System Simulation Experiments (OSSE)

Truth run: **Hurricane Karl**, 21Z 16 – 00Z 18 SEP 2010
Resolution: **27, 9 & 3 km (D1-D3), EnKF only for D3**



EnKF Performance on IR Brightness Temperature

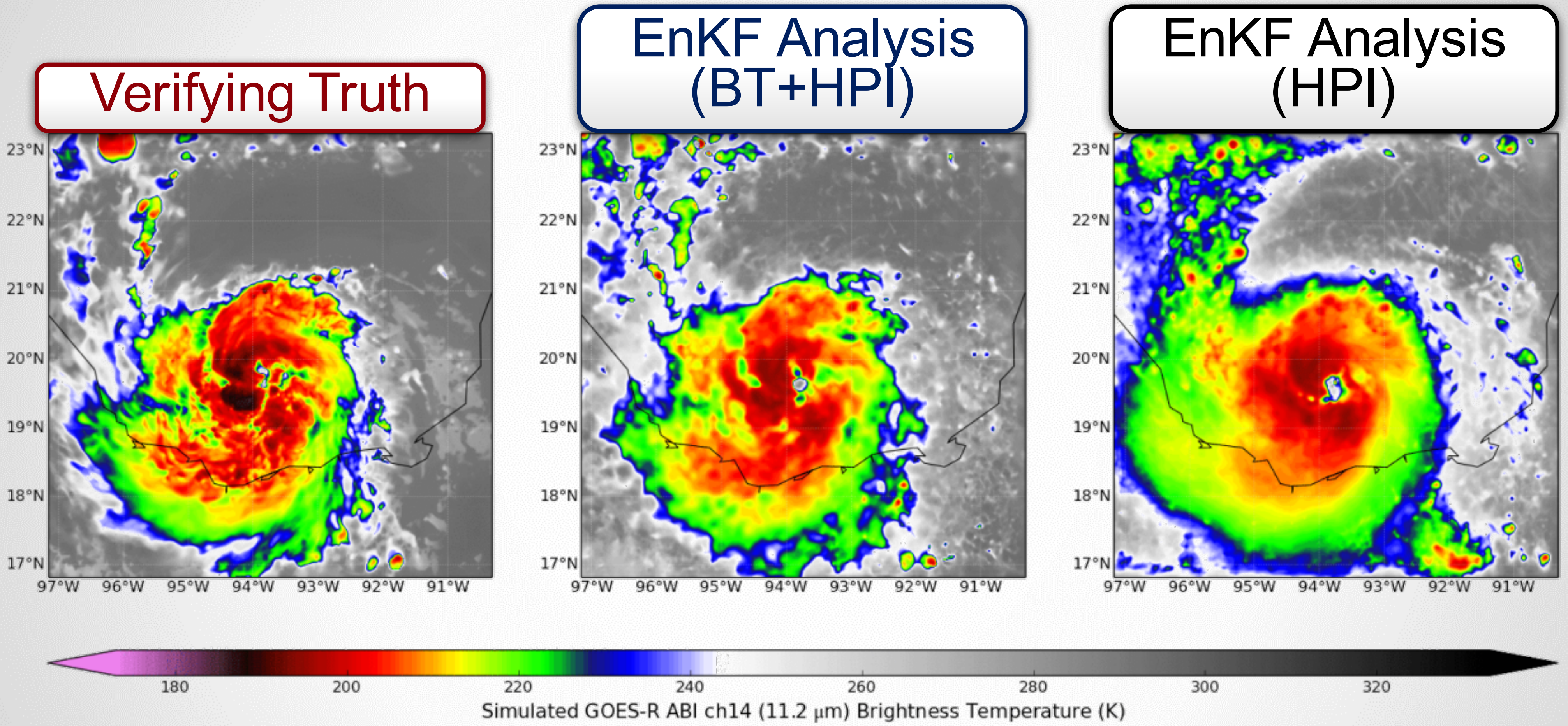
Brightness Temperature of GOES-R ABI Ch14 (11.2 μm)



Zhang, Minamide & Clothiaux, 2016, GRL

EnKF Performance on IR Brightness Temperature

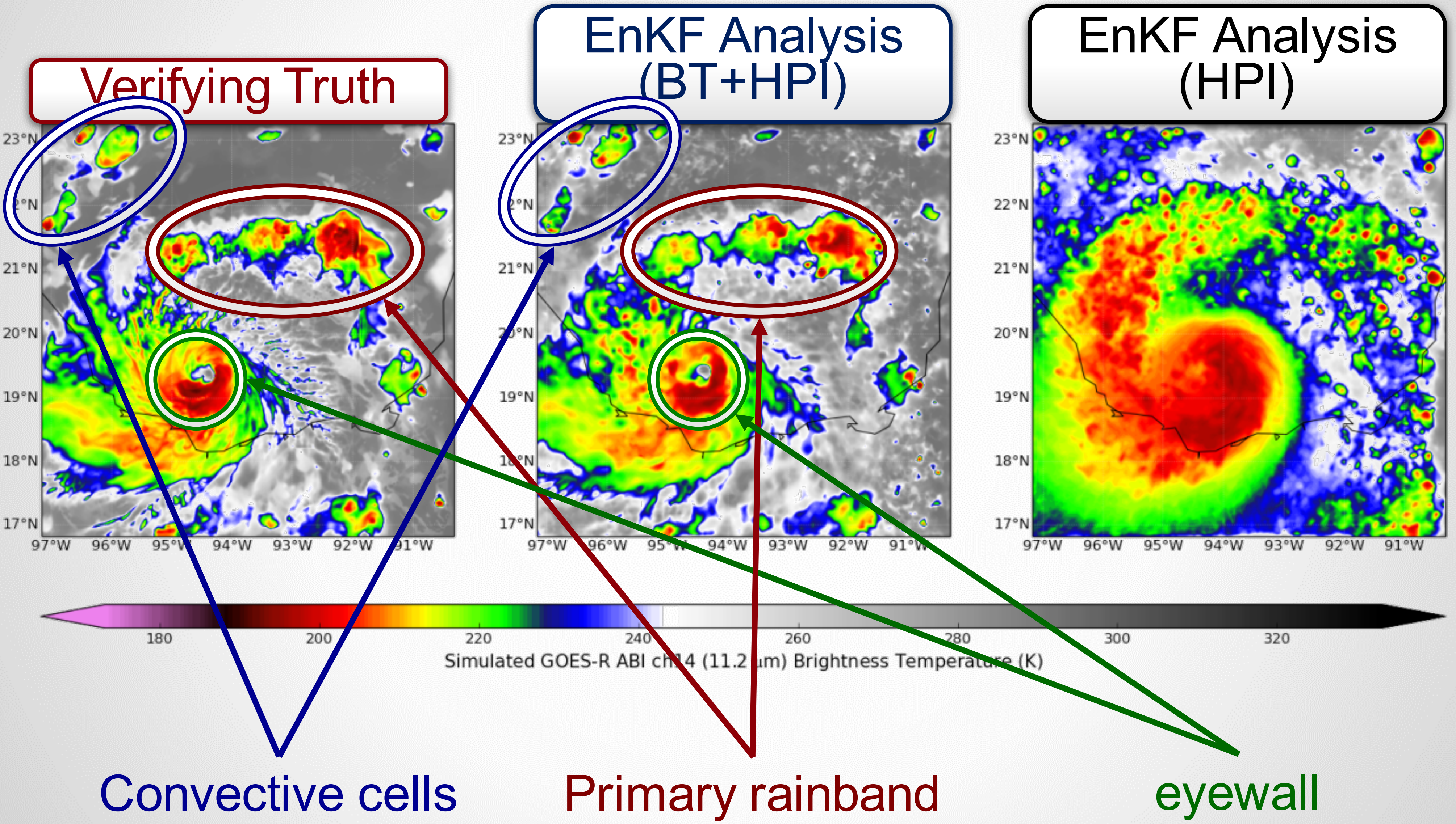
Brightness Temperature of GOES-R ABI Ch14 (11.2 μm)



Zhang, Minamide & Clothiaux, 2016, GRL

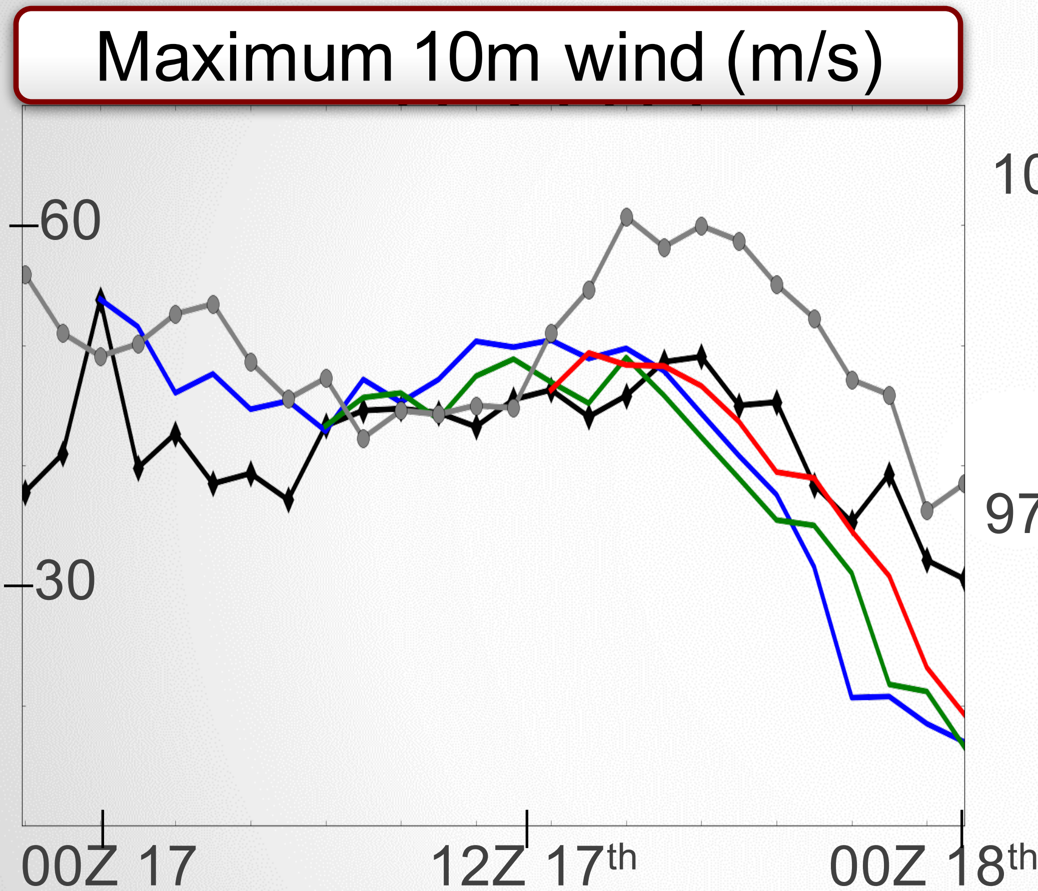
EnKF Performance on IR Brightness Temperature

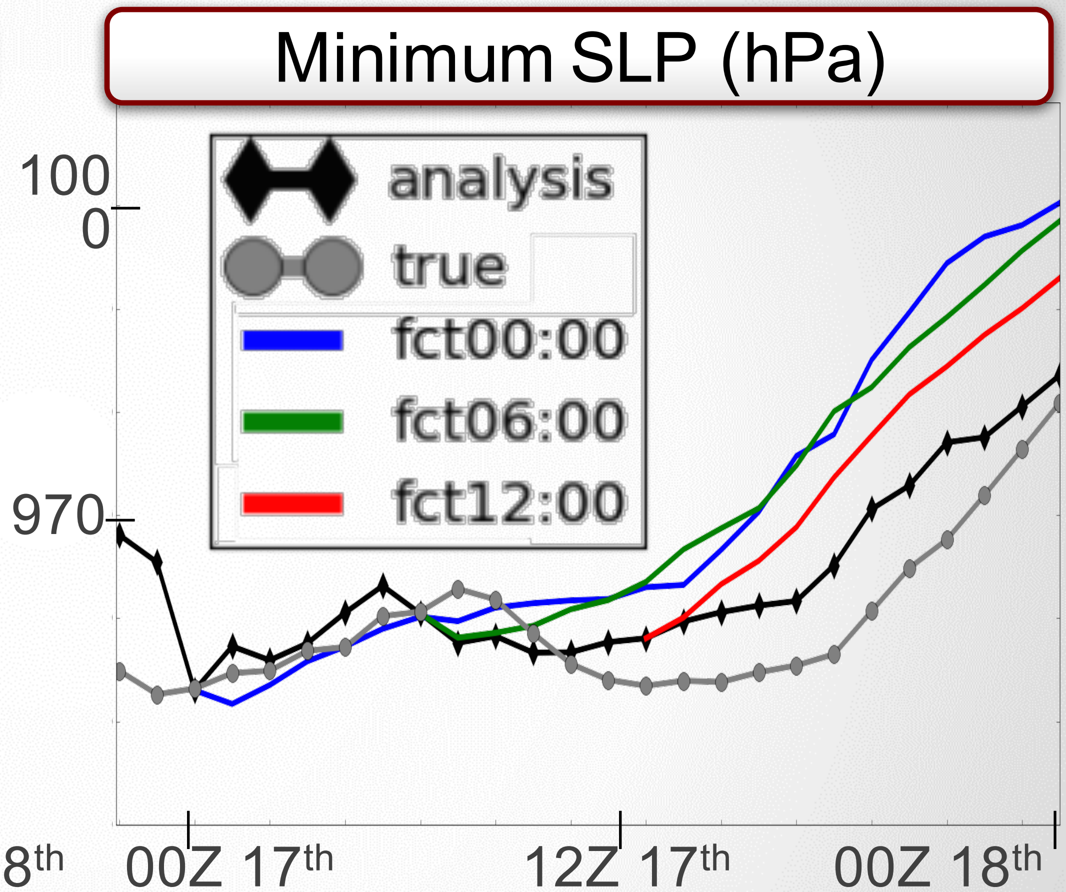
Brightness Temperature of GOES-R ABI Ch14 (11.2 µm)



Zhang, Minamide & Clothiaux, 2016, GRL

EnKF Performance on Tropical Cyclone Intensity

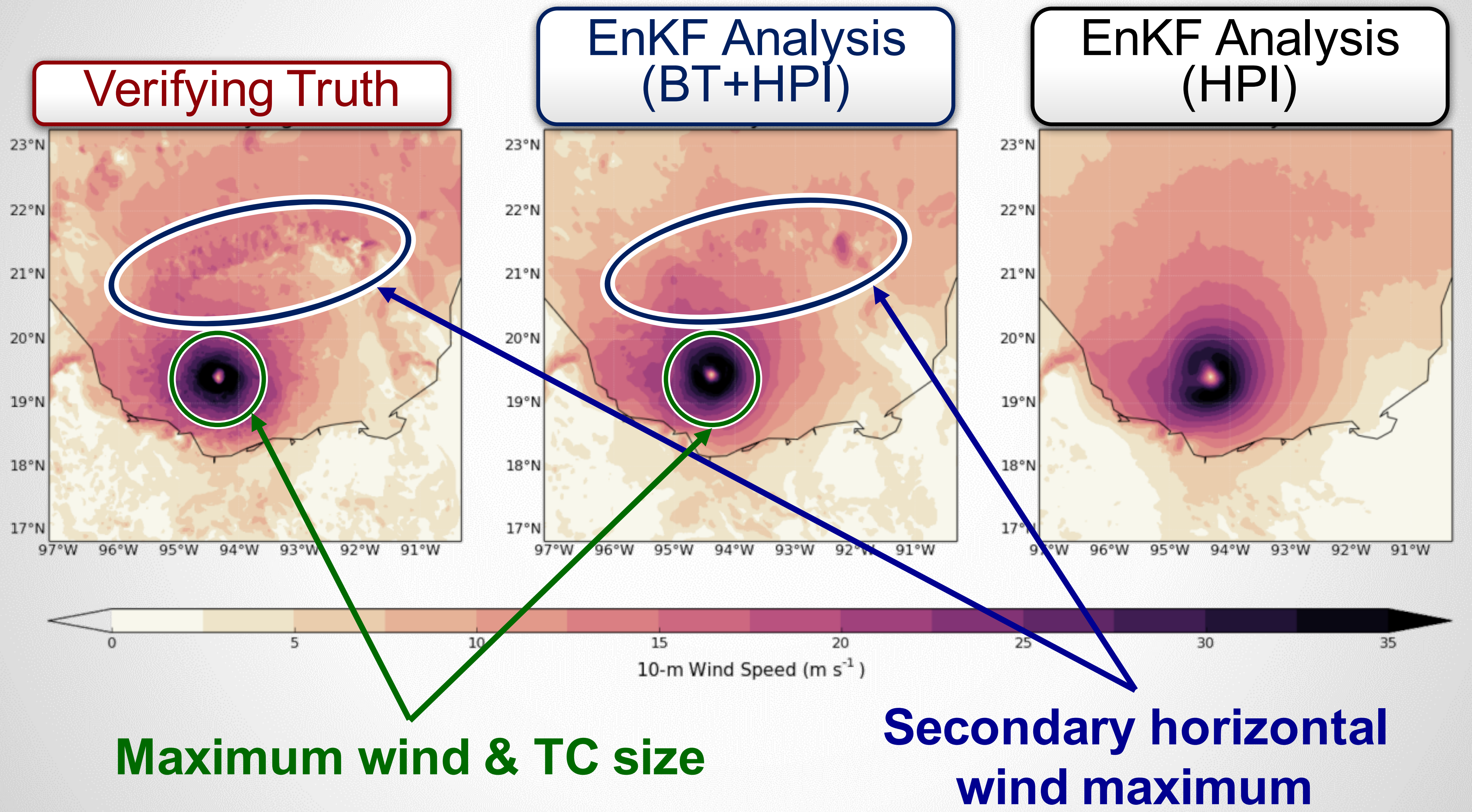




- The longer the assimilation, the better the analysis.
- Analysis is capable of capturing the intensity changes.

Zhang, Minamide & Clothiaux, 2016, GRL

EnKF Performance on 10-m wind speeds

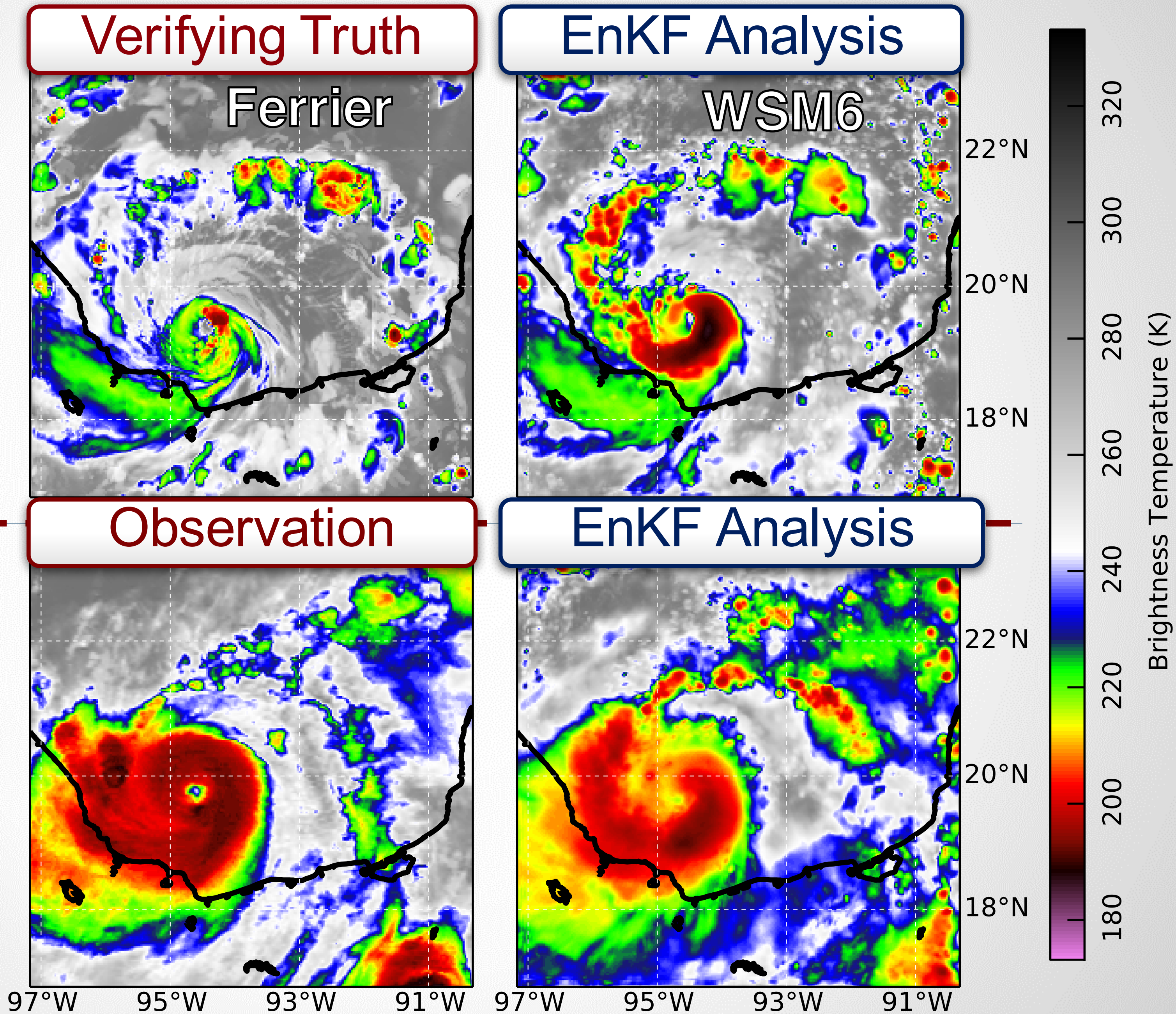


Zhang, Minamide & Clothiaux, 2016, GRL

EnKF Performances on Hurricane Karl (2010)

Imperfect-model OSSE

Real-data GOES-13 assimilation



Zhang, Minamide & Clothiaux, 2016, GRL

Concluding Remarks

- CRTM has been combined to the PSU WRF-EnKF to directly assimilate satellite infrared brightness temperature.
- OSSE and GOES-13 real-data assimilation experiments showed EnKF assimilation of all-sky infrared brightness temperature can well capture detailed structure of tropical cyclones.
- Assimilation of Himawari8-observed real-data is underway.

The CRTM with Microphysics Scheme-Consistent Cloud Optical Properties

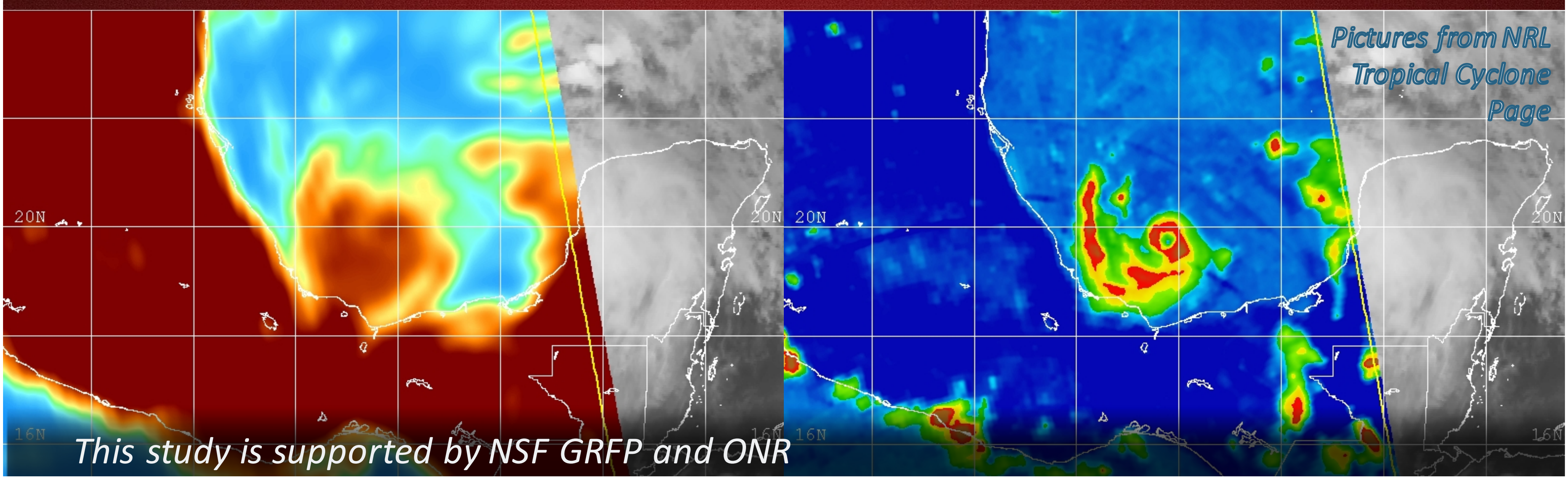
Scott Sieron,

Eugene Clothiaux and Fuqing Zhang

Department of Meteorology and

Center for Advanced Data Assimilation and Predictability Techniques (ADAPT),

The Pennsylvania State University



Motivation

- ■Initial goal: to assimilate precipitation-affected microwave imaging channels in regional-scale model (e.g., Zhang et al 2013), as Masashi is doing for IR
  - Good progress at global DA centers (e.g., Bauer et al. 2014, Kazumori et al. 2016)
- ■Had difficulty producing realistic CRTM microwave radiative transfer results in precipitation areas
  - Fixed effective radii with values based on literature (~1000 μm) → too much scattering
  - Mean particle size as effective radius → too little scattering

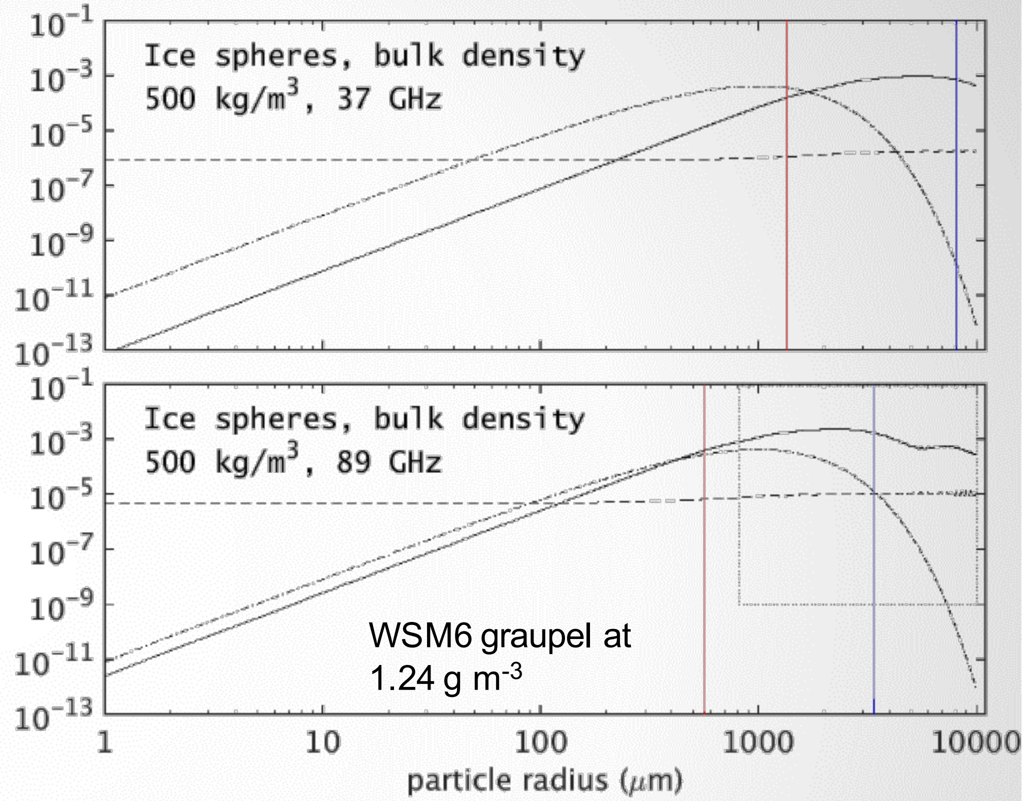
Motivation

■Desired cloud scattering in the CRTM to be consistent with our mesoscale NWP model (WRF) output

- Either *monodisperse* or using *generalized gamma* particle size distribution (PSD):

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

- Marshall-Palmer (1948) distribution: $\mu = 0$

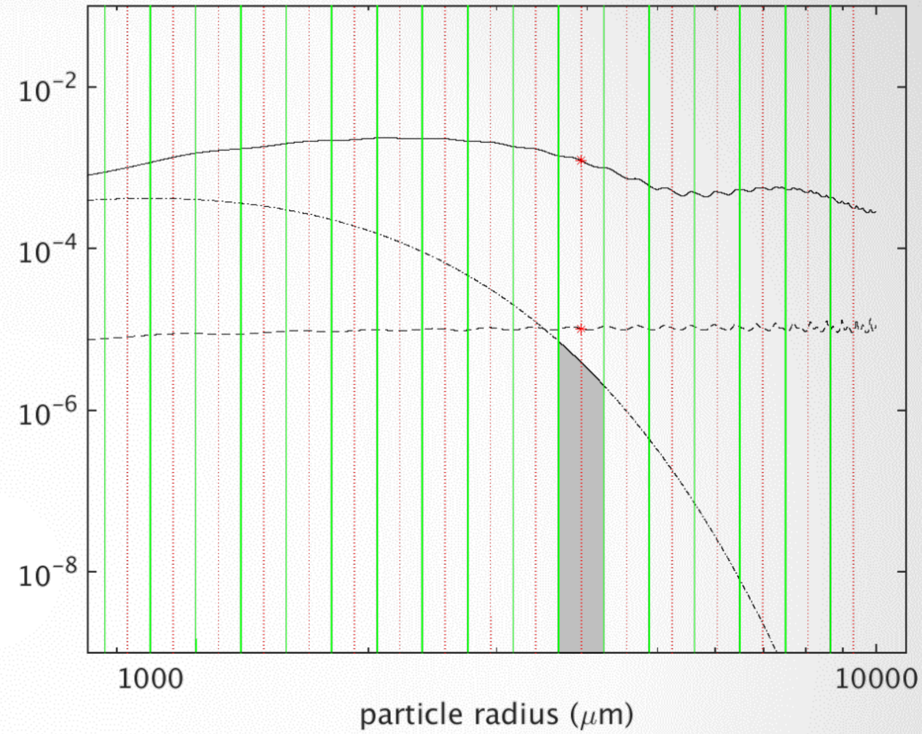


Solid: scattering coeff. ($m^2\ kg^{-1}$)
Dashed: absorption coeff. ($m^2\ kg^{-1}$)
Dot-dashed: sample particle mass distribution ($kg\ m^{-3}\ \mu m^{-1}$) of graupel-like ice spheres

Blue: wavelength
Red: one-sixth wavelength

Scheme-Specific Cloud Optical Properties

Our solution: new cloud optical property lookup tables in CRTM



- Method 1, "Distribution-Specific": scheme-specific cloud scattering property lookup tables
- Method 2, "Generalized-Bin": particle scattering property lookup tables
  - Scheme information and integration of particle size distributions within CRTM

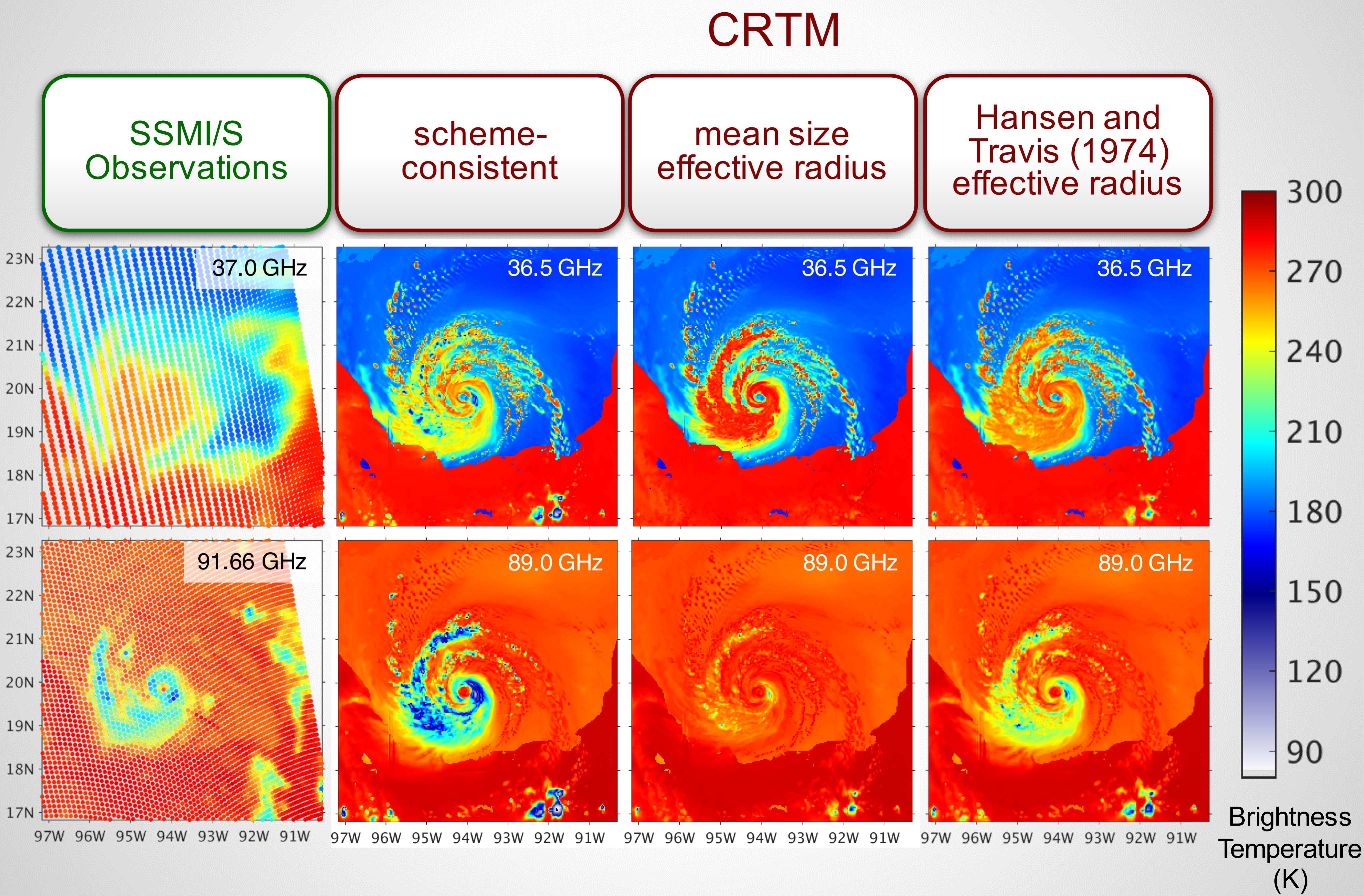
- Mie theory single-particle scattering by soft spheres as specified by schemes

Experiments

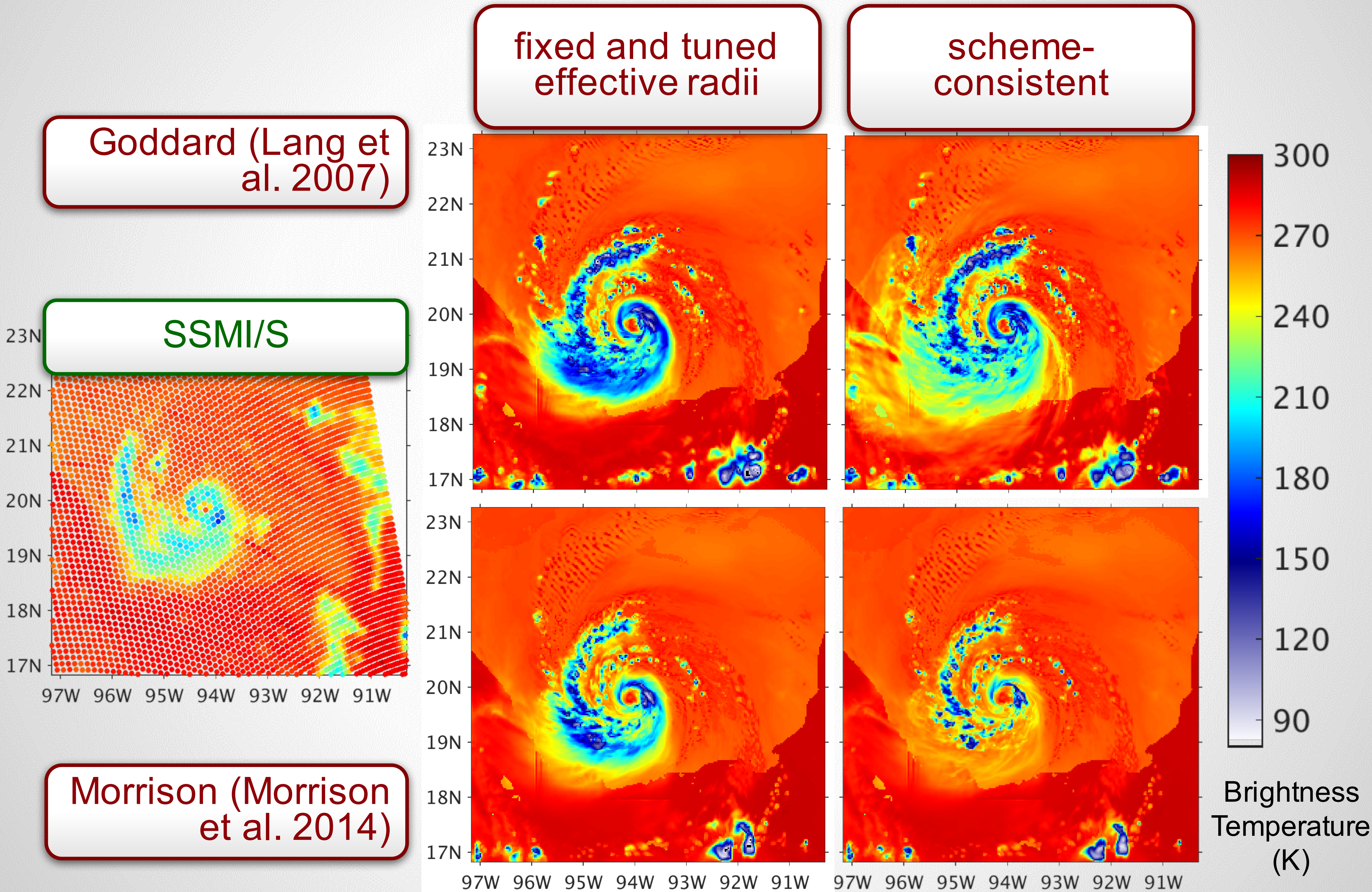
Use model forecast output from Hurricane Karl EnKF analysis (3-hour forecast, 3 km grid spacing domain):

- Modified CRTM, Distribution-Specific (Method 1)
- Modified CRTM, Generalized-Bin (Method 2)
  - 32, 64 or 128 bins spaced log-linearly between 1 μm and 10000 μm
- Unmodified CRTM (effective radii)
  - Mean particle size: $r_{eff} = (\mu + 1)\lambda^{-1}$
  - Mean radius for scattering (Hansen and Travis 1974): $r_{eff} = (\mu + 3)\lambda^{-1}$
  - Prescribed for each species, uniform in space
    - Values chosen to produce simulations matching well to observations and be physically reasonable

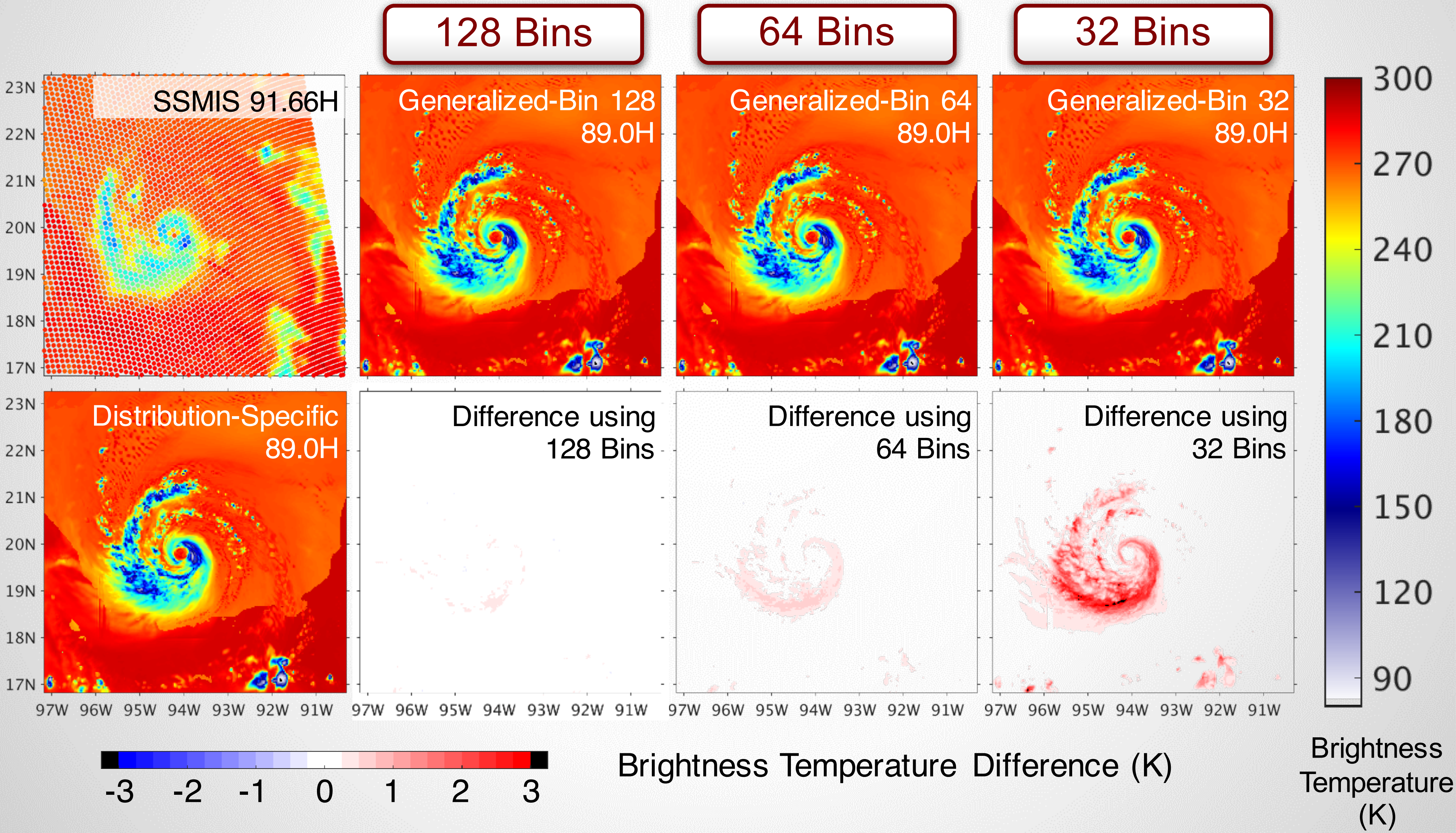
Results, WSM6 Scheme



Results, Morrison and Goddard Schemes



Generalized-Bin Results (WSM6)



Concluding Remarks

- Successful scheme-consistent cloud radiative properties in the CRTM
  - Simulation bias to observations (too much scattering) consistent with to other radar and passive microwave studies
- Brightness temperatures more similar to observations are possible with unmodified CRTM
  - Apparently compensating for errors in CRTM and microphysics
- Scheme-consistent cloud scattering necessary for model evaluation/constraining with observations

References

Kazumori, M., A. J. Geer and S. J. English, 2016: Effects of all-sky assimilation of GCOM-W/AMSR2 radiances in the ECMWF numerical weather prediction system. *Quart. Jour. Roy. Meteor. Soc.*, **142**, 721–737.

Liu, Q., and F. Weng, 2006: Advanced doubling-adding method for radiative transfer in planetary atmospheres. *J. Atmos. Sci.*, **63**, 3459–3465.

Marshall, J.S. and W. McK. Palmer, 1948: The Distribution of Raindrops with Size. *J. Meteor.*, **5**, 165–166

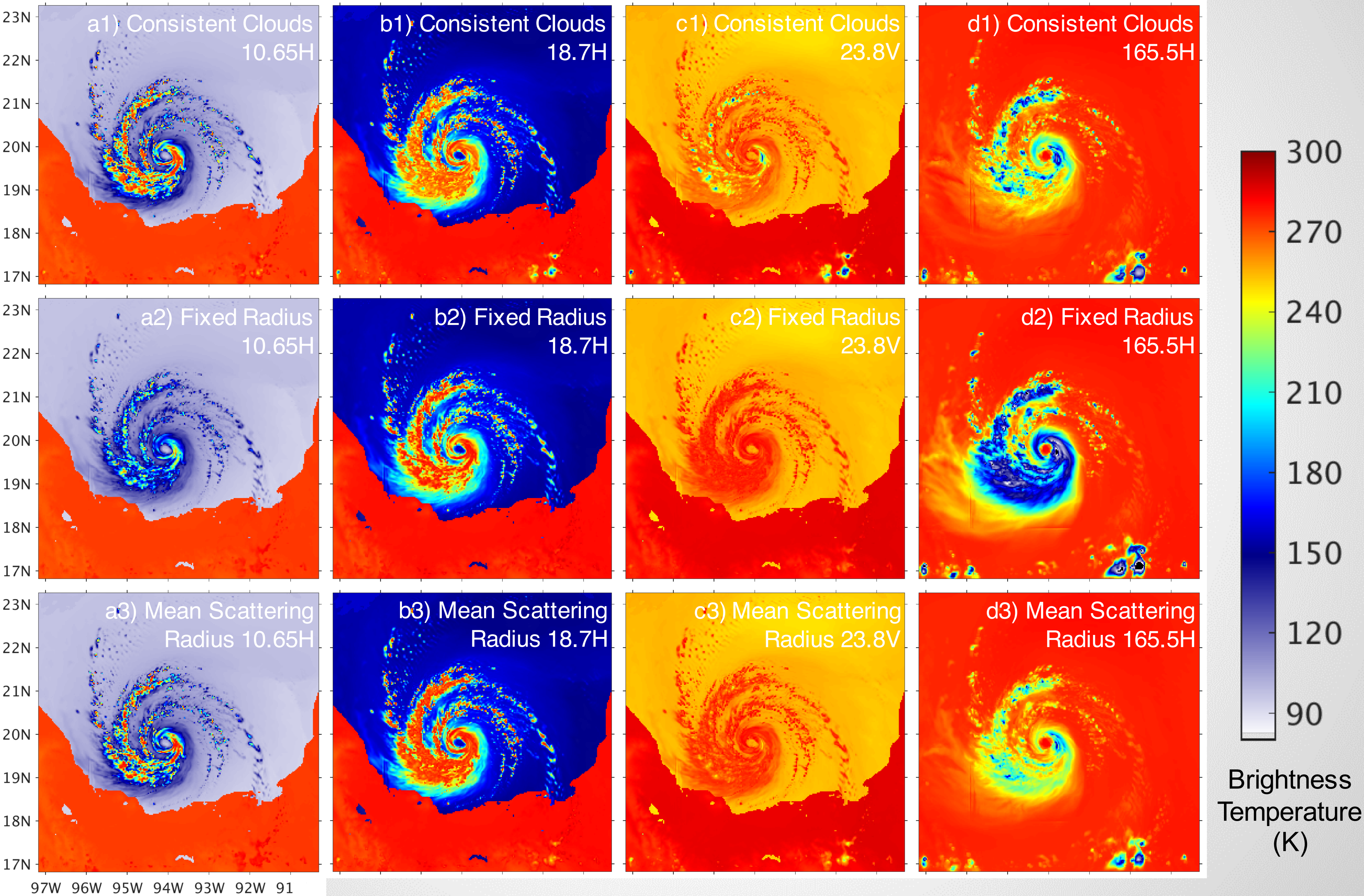
Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X.-Y. Huang, W. Wang, and J. G. Powers, 2008: A description of the Advanced Research WRF version 3. NCAR Technical Note 475, http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf.

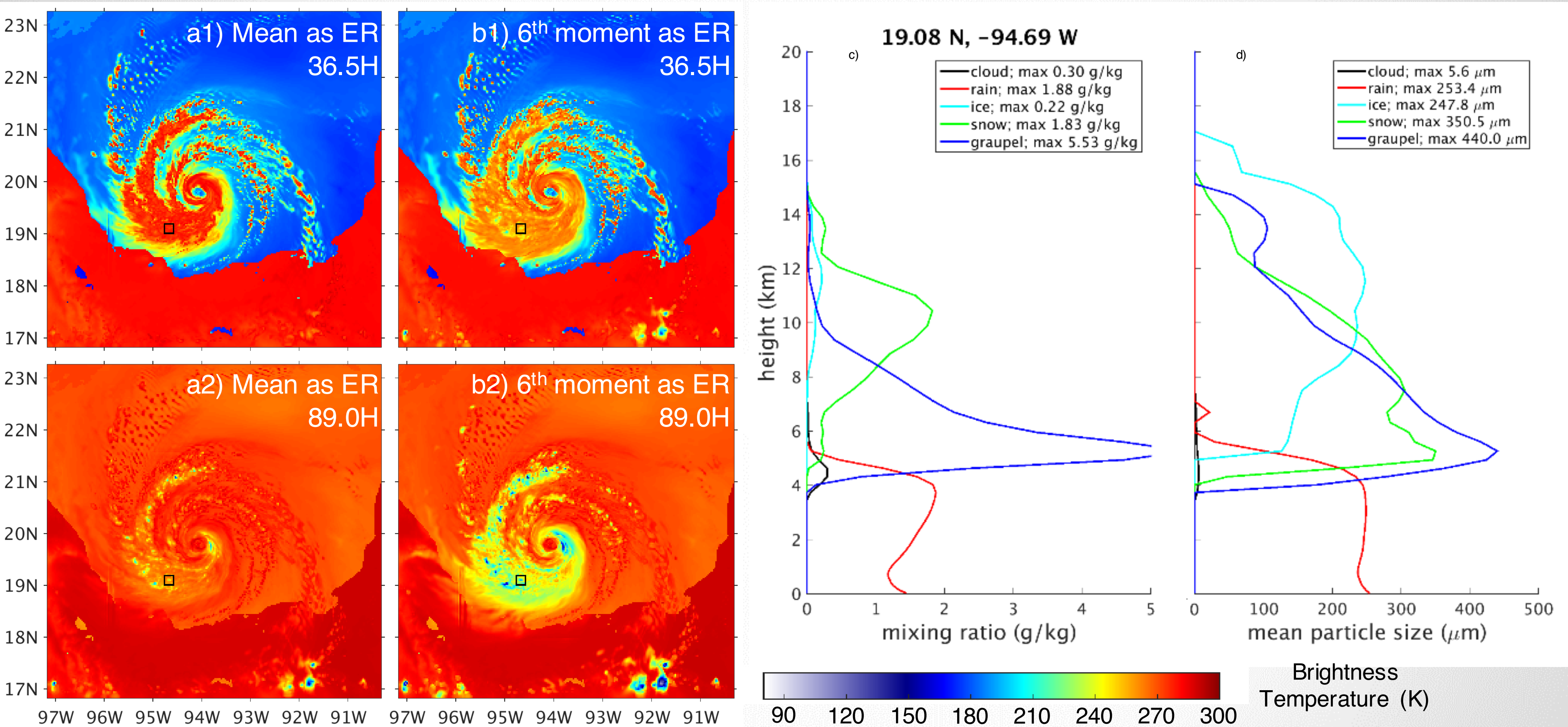
Weng, Y., and F. Zhang, 2012: Assimilating Airborne Doppler Radar Observations with an Ensemble Kalman Filter for Convection-permitting Hurricane Initialization and Prediction: Katrina (2005). *Mon. Wea. Rev.*, **140**, 841-859.

Zhang, S. Q., M. Zupanski, A. Y. Hou, X. Lin, and S. H. Cheung, 2013: Assimilation of Precipitation-Affected Radiances in a Cloud-Resolving WRF Ensemble Data Assimilation System. *Mon. Wea. Rev.*,**141**, 754–772.

Concluding Remarks

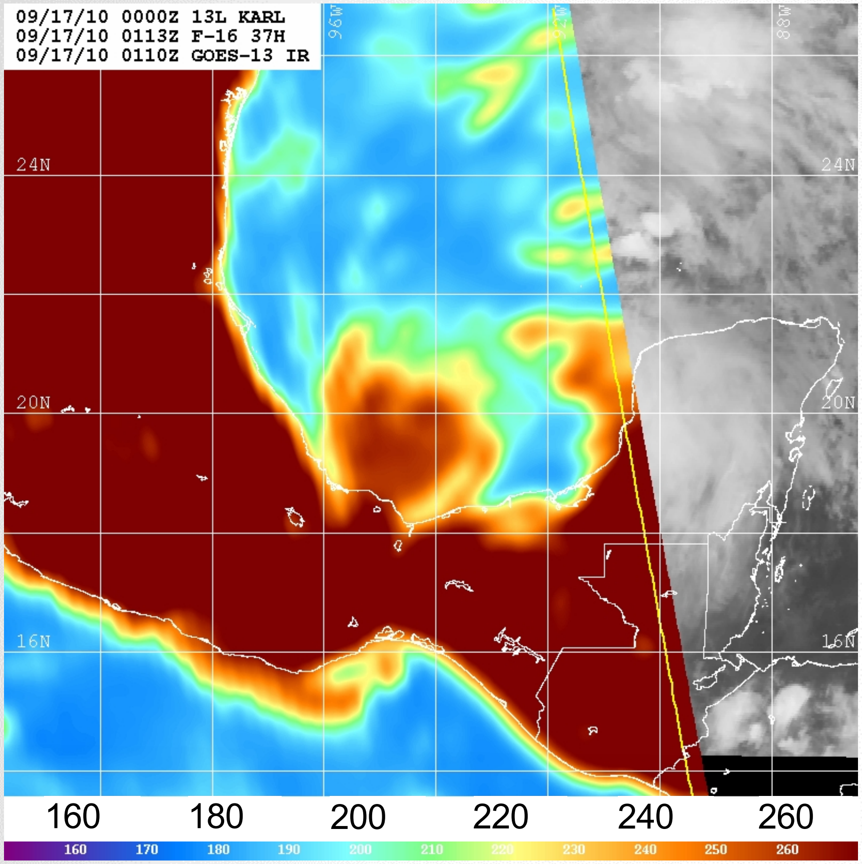
- Assimilation of precipitation information can be productive with cloud scattering inconsistent with microphysics schemes
  - Particle shape and bulk density is first priority; it will be a
- Constraining microphysics schemes with remote sensing data?
  - Will require accurate radiative transfer in all components. Can it be fast enough for operations?
  - Can microphysics be sufficiently accurate and complex? (Field et al. 2007)
  - Constrain both physical attributes and processes?
- As microphysics improve, scheme-consistent cloud scattering should provide optimal data assimilation
  - Particle size distributions is first priority
  - Habit prediction is probably necessary, has potential (citations)


a1) Consistent Clouds 10.65H
b1) Consistent Clouds 18.7H
c1) Consistent Clouds 23.8V
d1) Consistent Clouds 165.5H
a2) Fixed Radius 10.65H
b2) Fixed Radius 18.7H
c2) Fixed Radius 23.8V
d2) Fixed Radius 165.5H
a3) Mean Scattering Radius 10.65H
b3) Mean Scattering Radius 18.7H
c3) Mean Scattering Radius 23.8V
d3) Mean Scattering Radius 165.5H
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91
300 270 240 210 180 150 120 90
Brightness Temperature (K)


a1) Mean as ER 36.5H
b1) 6th moment as ER 36.5H
a2) Mean as ER 89.0H
b2) 6th moment as ER 89.0H
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W
19.08 N, -94.69 W
c)
d)
height (km)
mixing ratio (g/kg)
mean particle size (µm)
cloud; max 0.30 g/kg
rain; max 1.88 g/kg
ice; max 0.22 g/kg
snow; max 1.83 g/kg
graupel; max 5.53 g/kg
cloud; max 5.6 µm
rain; max 253.4 µm
ice; max 247.8 µm
snow; max 350.5 µm
graupel; max 440.0 µm
90 120 150 180 210 240 270 300
Brightness Temperature (K)

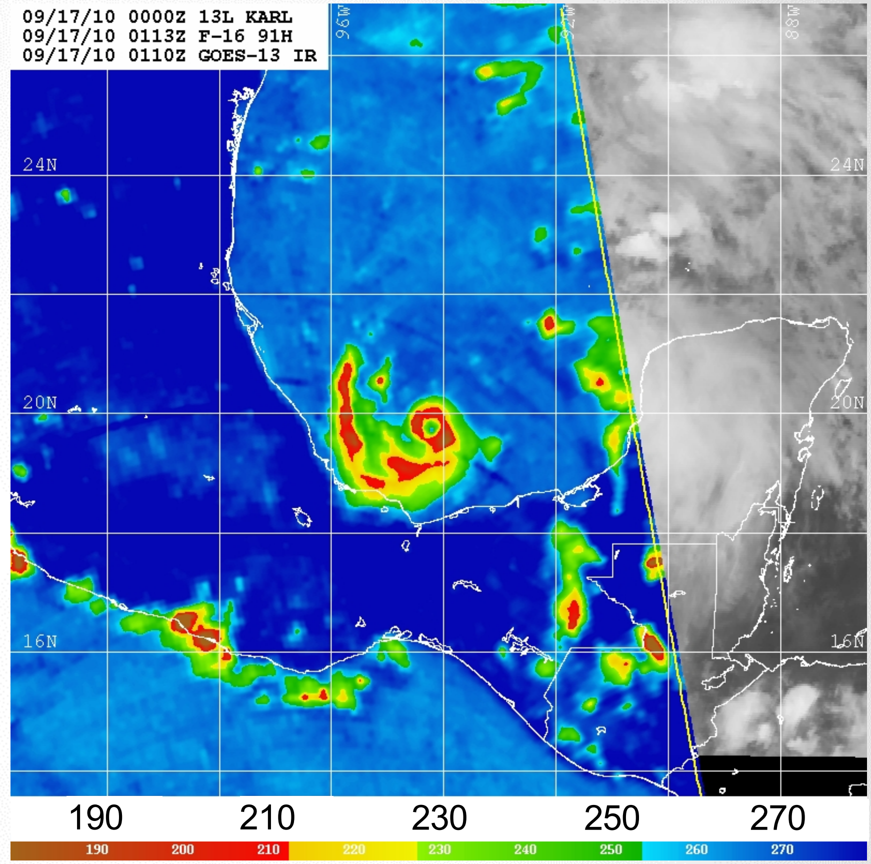
Microwave Radiometers and Precipitation

Low-mid microwave freq. (37 GHz)



COLD Brightness Temperature (K) WARM

High-mid microwave freq. (91.7 GHz)



COLD Brightness Temperature (K) WARM

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

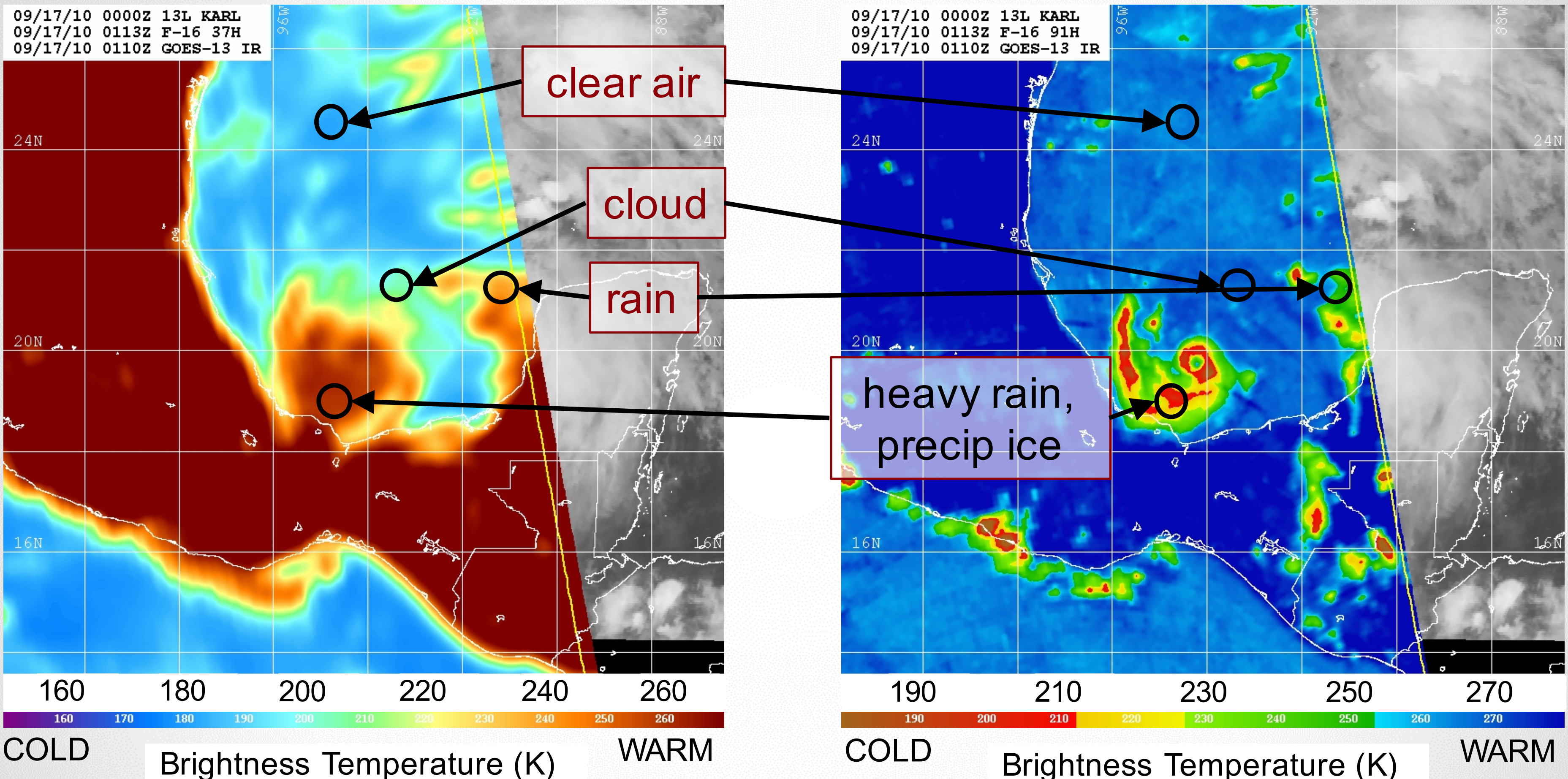
- Rain and cloud liquid net add to low water surface emission
- Some scattering by precipitation ice

- Scattering by precipitation ice dominates the signal

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

Experiments

Use model output from same Hurricane Karl EnKF analysis (3-hour forecast, 3 km grid spacing domain):

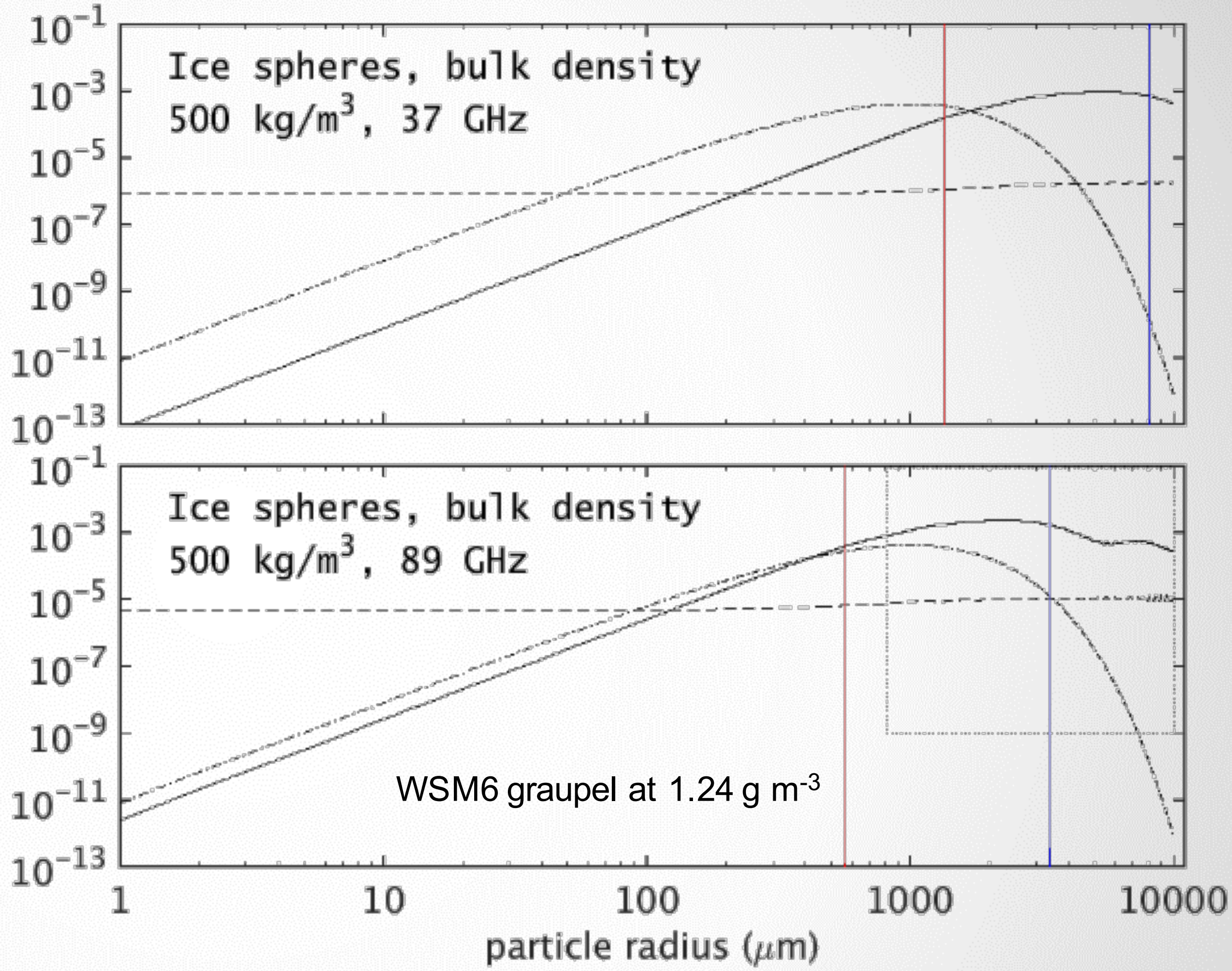
- Modified CRTM, Distribution-Specific (Method 1)
- Modified CRTM, Generalized-Bin (Method 2)
  - 32, 64 or 128 bins spaced log-linearly between 1 μm and 10000 μm
- CRTM with effective radii
  - Mean particle size; for generalized gamma particle size distribution,

    $r_{eff} = (\mu + 1)\lambda^{-1}$ ($\mu = 0$ for Marhsall and Palmer (1948))
  - Mean radius for scattering assuming r^2 relationship of particle size to scattering (Hansen and Travis 1974)

    $r_{eff} = \frac{\int r^3 N(r)dr}{\int r^2 N(r)dr}$; for generalized gamma, $r_{eff} = (\mu + 3)\lambda^{-1}$.
  - Prescribed for each species, uniform in space
    - Values chosen to produce simulations matching well to observations and be physically reasonable

Microwave, Sensitivity to Particle Size

- Strong dependence of particle size to scattering: r^6 for 3D particles much smaller than the wavelength
  - Many passive microwave radiometer wavelengths are close to the size of a significant mass of hydrometeors



Mass scattering (solid) and absorption (dashed) coefficients (m^2 kg^{-1}) and sample particle mass distribution (dot-dashed; kg m^{-3} μm^{-1}) of graupel-like ice spheres. Wavelength (blue) and one-sixth the wavelength (red) shown for reference.

Concluding Remarks

- Sufficiently accurate radiative transfer would pin the discrepancy to observations onto the NWP model
  - Not there yet with CRTM
- Sufficiently accurate and complex microphysics scheme required for scheme-consistent radiative transfer results to well-resemble observations
  - Probably not there yet with microphysics available in WRF
  - Habit prediction (Morrison et al. 2015), 1-moment bin (Khain et al. 2010), 2-moment bin

Mesoscale NWP Microphysics

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

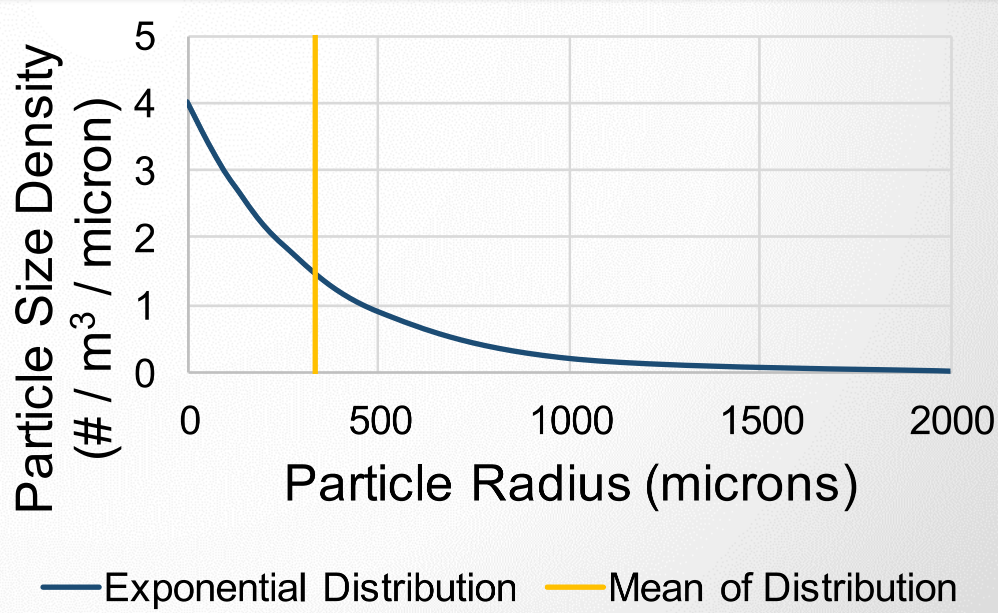
$$N(r) = N_0 r^{\mu} \exp(-\lambda r),$$

  - Common is Marshall-Palmer (1948) 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})



Motivation

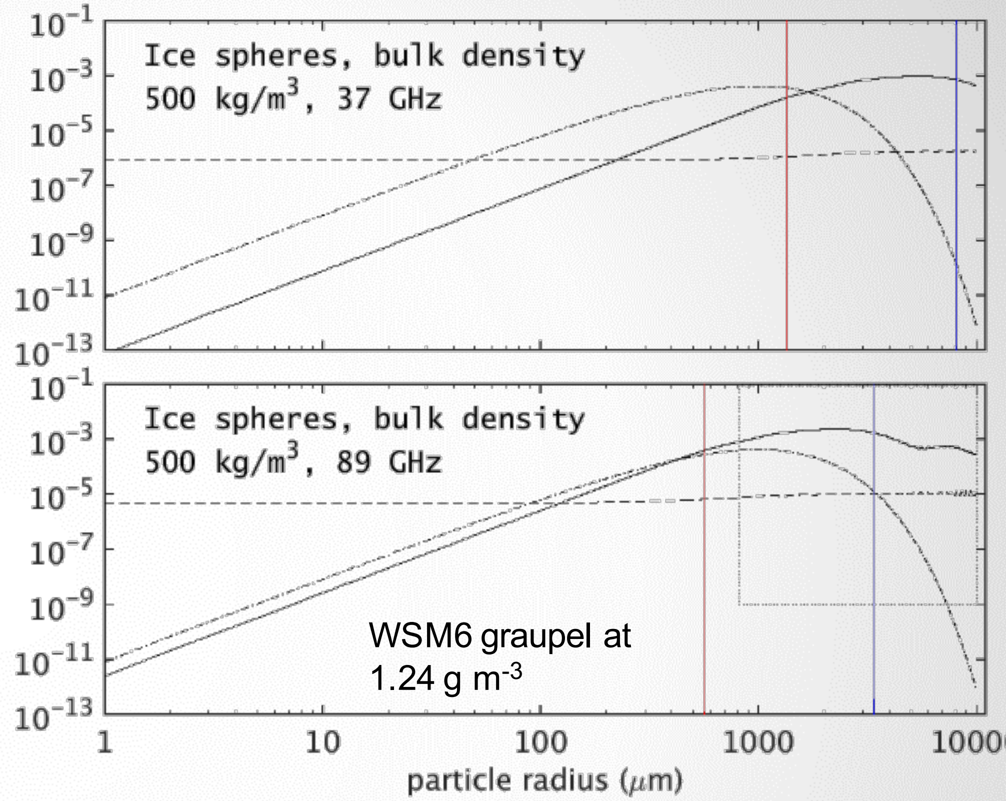
- WRF output provides cloud species and mass, but no particle size information for assigning effective radii (must obtain from literature and source code)
  - Most bulk species are assumed monodisperse, or having a generalized gamma particle size distribution (PSD):

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

    - Common is Marshall-Palmer (1948) distribution: $\mu = 0$
- Did not know how to best interface microphysics schemes to the CRTM via effective radius
  - There is little CRTM documentation on effective radius
  - Assume it relates in some way to a generalized gamma particle size distribution (perhaps monodisperse for cloud water and ice)

Motivation

- Even when using the most appropriate effective radius, cloud scattering may be inconsistent
  - Differences in particle shapes, bulk densities and size distributions are relevant (e.g., Geer and Baordo 2014, Mitchel 2001)
    - e.g, WSM6: graupel bulk density, snow particle size distribution



Mass scattering (solid) and absorption (dashed) coefficients ($m^2\ kg^{-1}$) and sample particle mass distribution (dot-dashed; $kg\ m^{-3}\ \mu m^{-1}$) of graupel-like ice spheres. Wavelength (blue) and one-sixth the wavelength (red) shown for reference.

- Our solution: new cloud optical property lookup tables in CRTM

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.