Observing System Simulation Experiments for Convective Clouds

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(and the A+CCP Science Impacts Team)

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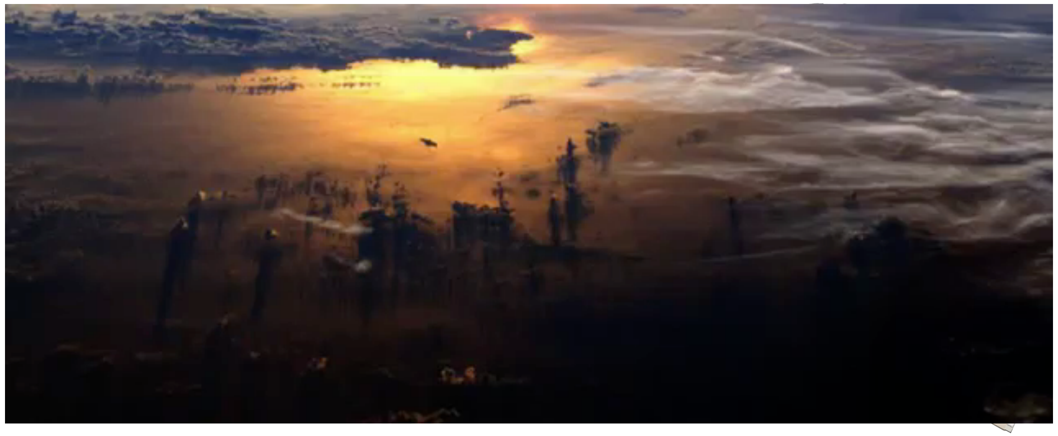
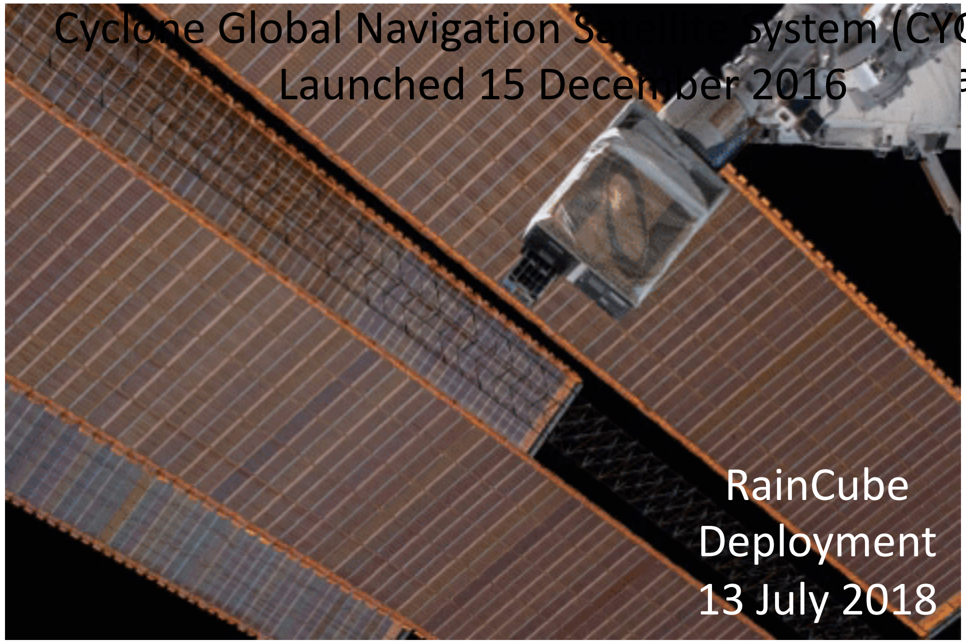
Modern Satellite Mission Design

- Technological advances (especially cube-sat and small-sat) have greatly expanded the trade space for satellite mission design
- There are increasing demands to demonstrate (quantitatively) the value of a new set of measurements in advance
- Especially important to evaluate constellations of small satellites
- There is room for innovation in the design of experiments and evaluation of measurement impact.



Cyclone Global Navigation Satellite System (CYGNSS)
Launched 15 December 2016

adar



RainCube
Deployment
13 July 2018

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Aerosols, Clouds, Convection, and Precipitation (A+CCP)

- Designated observables from 2017 Decadal Survey
- Dynamic cloud systems are important and not as well observed as we would like
  - Produce all of the Earth's fresh water (support of human society, input to surface hydro)
  - Source of largest atmospheric climate uncertainties
- Aerosol distribution and properties and interactions with clouds are highly uncertain
- Science foci (specific to CCP)
  - Relate cloud properties to precipitation processes and radiative forcing
  - Understand how convective dynamics and vertical transport are connected to cloud and precipitation properties
- Prior to KDP-A, conduct extensive architecture studies
- These take the form of a spectrum of observing system simulation experiments
- **Program of record will be part of the mission**

Quantifying Observational Requirements
Observing System Simulation Experiments (OSSEs)

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OSSEs for CCP: Specific Considerations

- **Goal: assess the degree to which specific measurements:**
  - Achieve the observing system desired capability
  - Address the science goals and objectives
- **Forecast OSSEs for convective processes and at convective scales have limitations**
  - Data assimilation for clouds, convection and precipitation is challenging (nonlinearity, representativeness, rapid temporal evolution)
  - Addressing a science objective may not lead to forecast improvement (and vice versa)
  - Forecast OSSEs would not leverage the existing field campaign data archive
- ***However*, forecast OSSEs consider the program of record** (assuming PoR is simulated accurately…)

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OSSEs for CCP: Key Objectives

1. Assess **sampling**
   1. Is a single observatory sufficient, or is a train / convoy needed?
   2. What are the tradeoffs among swath width, footprint size, and sensitivity/SNR?
2. Trace observables to science objectives
   1. Is uncertainty in **retrieved** geophysical quantities small enough to identify signals of interest?
   2. Do measurements reduce uncertainty in a **process** or outcome of a process (**analysis/forecast**)?
3. Connect measurables to value (science outcomes, risk, cost)

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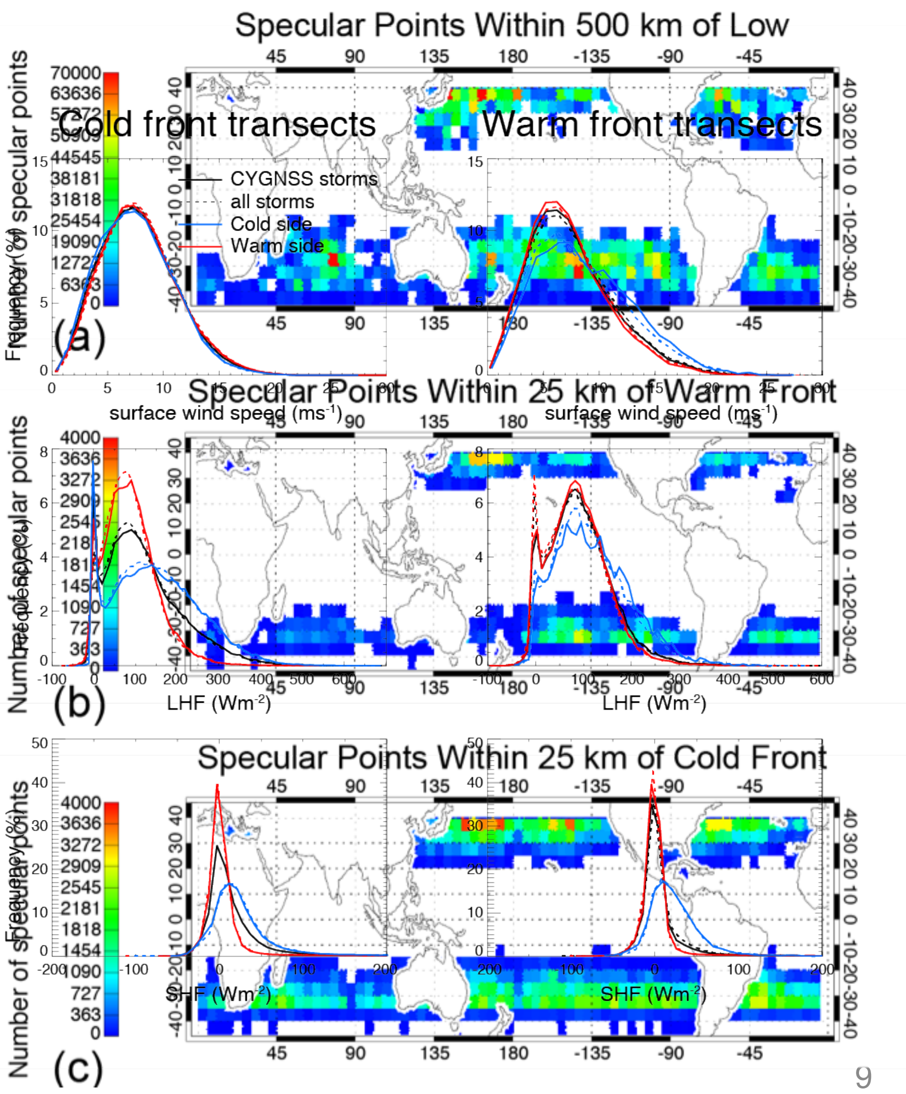
Sampling OSSE

- Determine orbital and/or swath characteristics
- Given a dataset that includes the feature(s) of interest, this is fast and simple
- Fundamental question: can the characteristics of a distribution be reproduced from a particular sub-sample?
- Compute statistics from a large dataset (e.g., a global nature run)
    - Full dataset
    - Sub-sample consistent with particular swath, resolution, and orbit
- Compare the distributions



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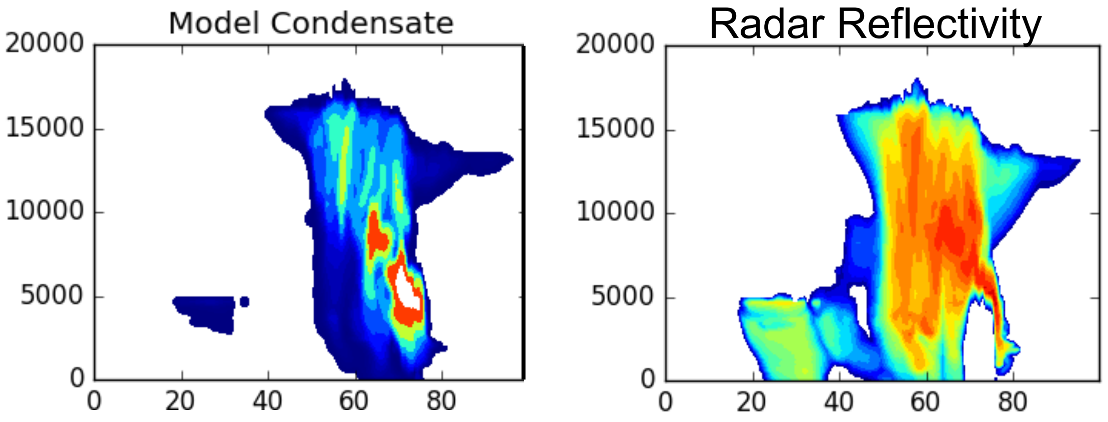
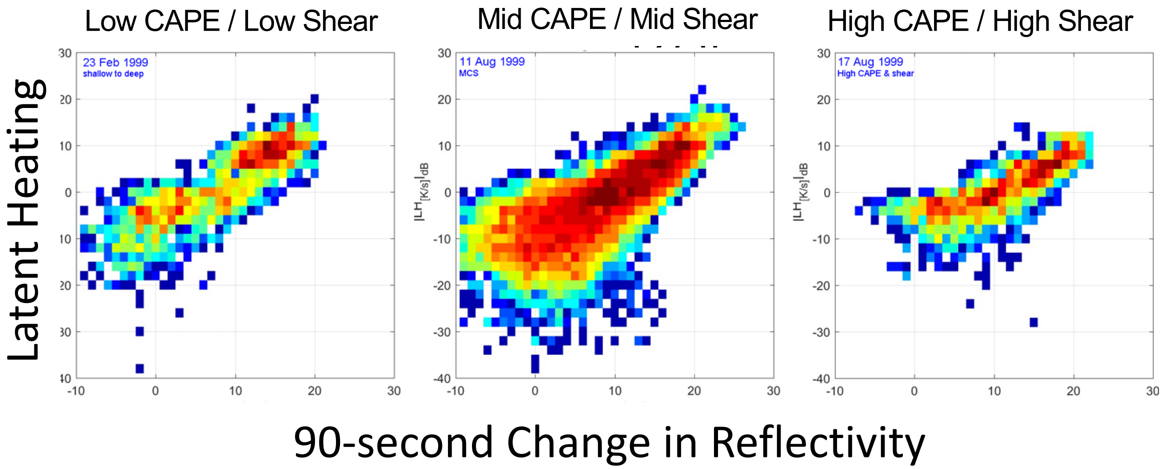
Retrieval OSSE

Use simulated atmospheric states + instrument simulators + retrieval algorithms to assess observability and uncertainty

- Step 1: use model + simulator
  - Rapidly assess relationships among geophysical quantities and measurements
  - Fast and simple, but does not place error bars on the retrieval



- Step 2: add a retrieval algorithm
  - Simulate measurements from specified state, then conduct retrieval
  - Vary obs types and uncertainties



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Retrieval Uncertainty Assessment

- Recall components of an OSSE:
  - Representation of nature
  - Simulation of observations
  - Quantitative measure of impact / effectiveness of measurements
- Observing system uncertainty experiment for cloud observables
  1. Define geophysical parameters of interest
  2. Set desired uncertainty bounds*
  3. Collect a list of candidate measurements**
  4. Perform simulated retrievals***
  5. Compare uncertainty in retrieval with desired uncertainty

* Quantifying this is a challenge
** Presumes the existence of accurate measurement simulators
*** Presumes the existence of a retrieval algorithm that produces estimates of uncertainty

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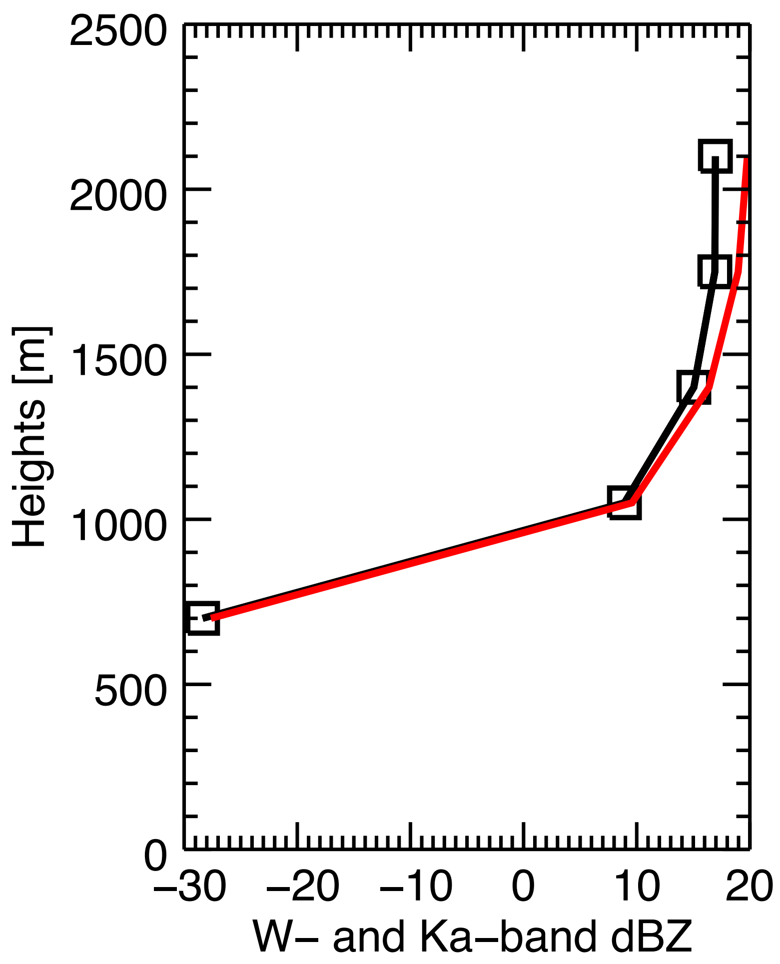
Drizzle Processes in Liquid Clouds

- Rain initiation in shallow clouds is crucial for climate feedbacks and remains poorly understood
- Depends on the size distribution of cloud and rain drops
- Conduct a retrieval OSSE to understand which observations are needed to inform cloud and rain droplet population
- Nature: in-situ (aircraft) obs of clouds
- Candidate measurements: active (radar) and passive (microwave and visible/near-IR)
- Measurement simulators readily available



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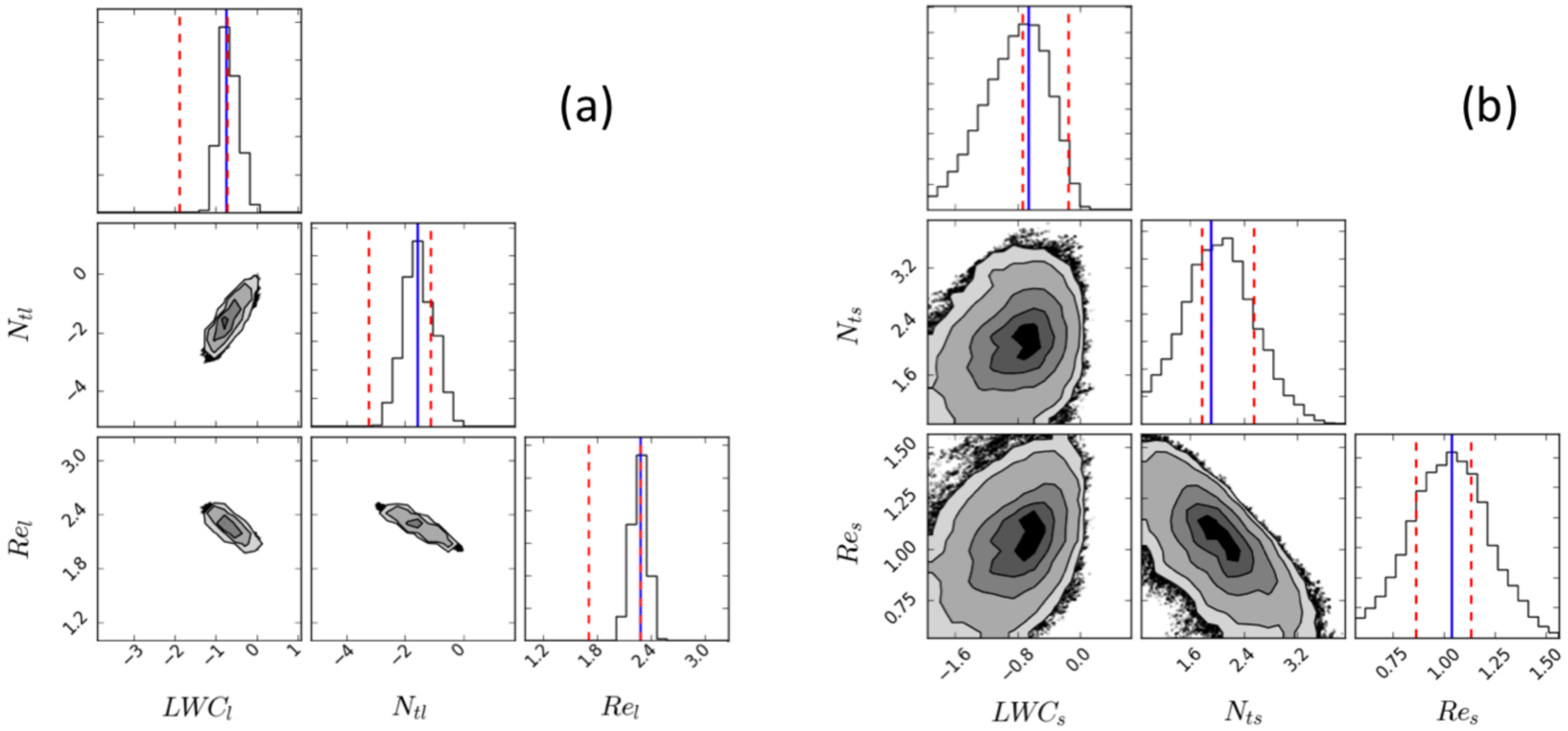
Retrieval

- In practice: optimal estimation
- Characterize information space using a Markov chain Monte Carlo (MCMC) algorithm
  - Sample of the probability distribution of retrieved states
  - Understand Gaussianity of solution
  - Flexible computation of error statistics
- Assess current observing system (CloudSat + MODIS)
- Test future observing system (dual frequency radar + microwave + reflectances)

Posterior Densities from MCMC

- Run MCMC for several candidate observing configurations
- Evaluate CloudSat vs notional CCP measurements



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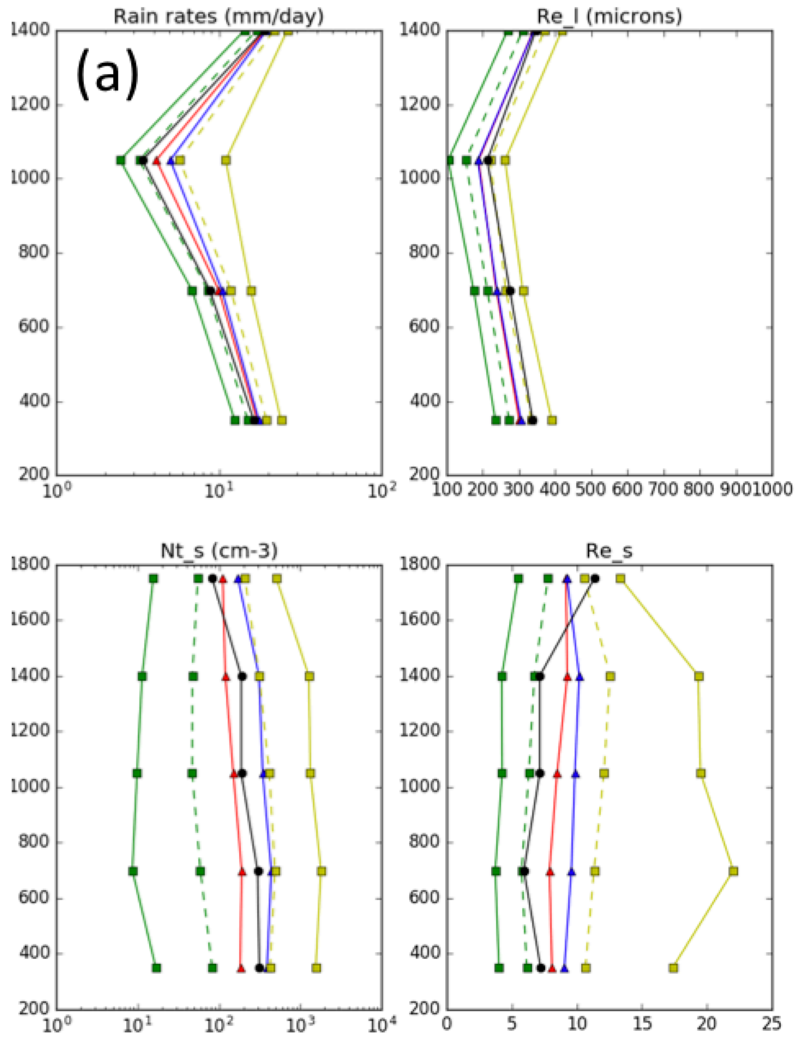
Statistics of Profiles

- Compare profiles
- Uncertainty represented in quantiles
- Addition of radar frequency provides significant constraint on the profile
- What is the role of the program of record?
- How much uncertainty is too much?



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Assess Measurement Uncertainty

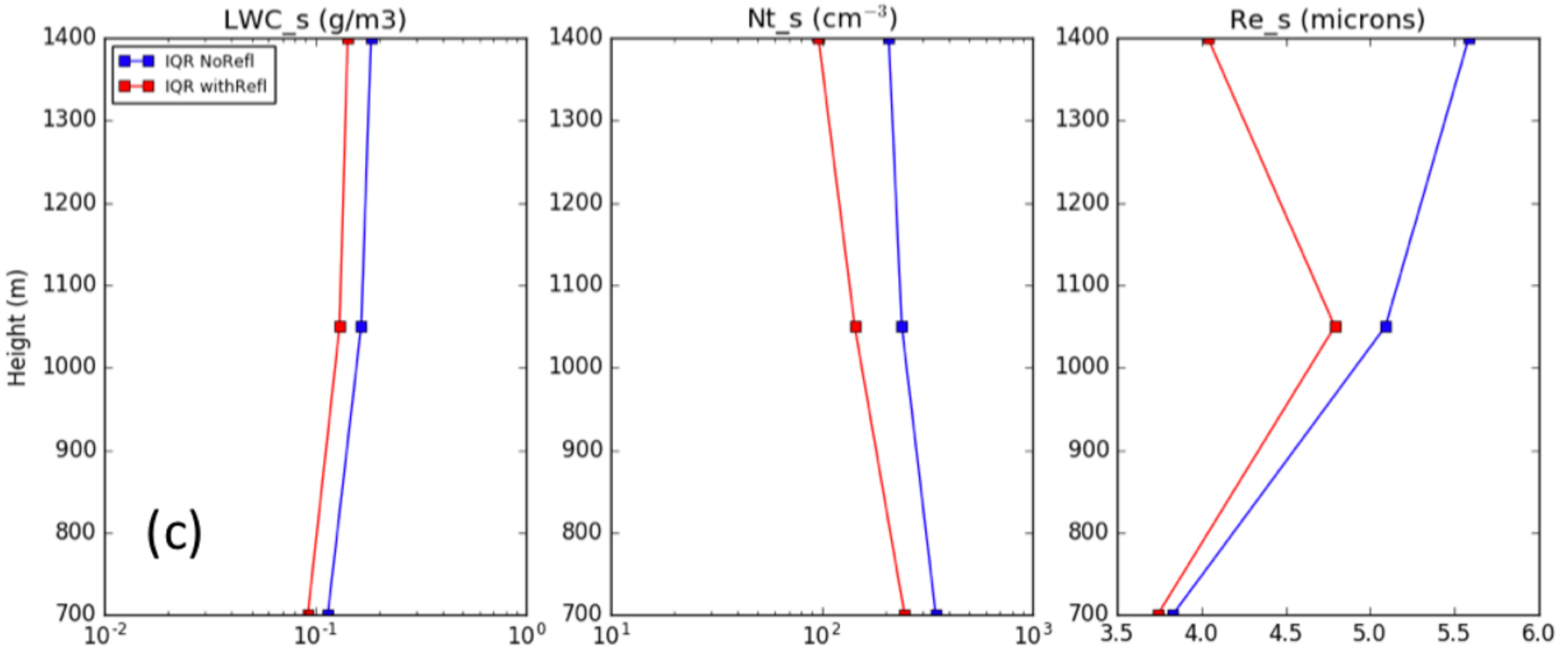
- Degrade radar and passive microwave measurements
- Ultimately, most information is provided by program of record (visible and near infrared reflectance)

Uncertainty:

a) 3 dB radar + 2 K Tb

b) 3 dB radar + 4 K Tb

c) 6 dB radar + 8 K Tb



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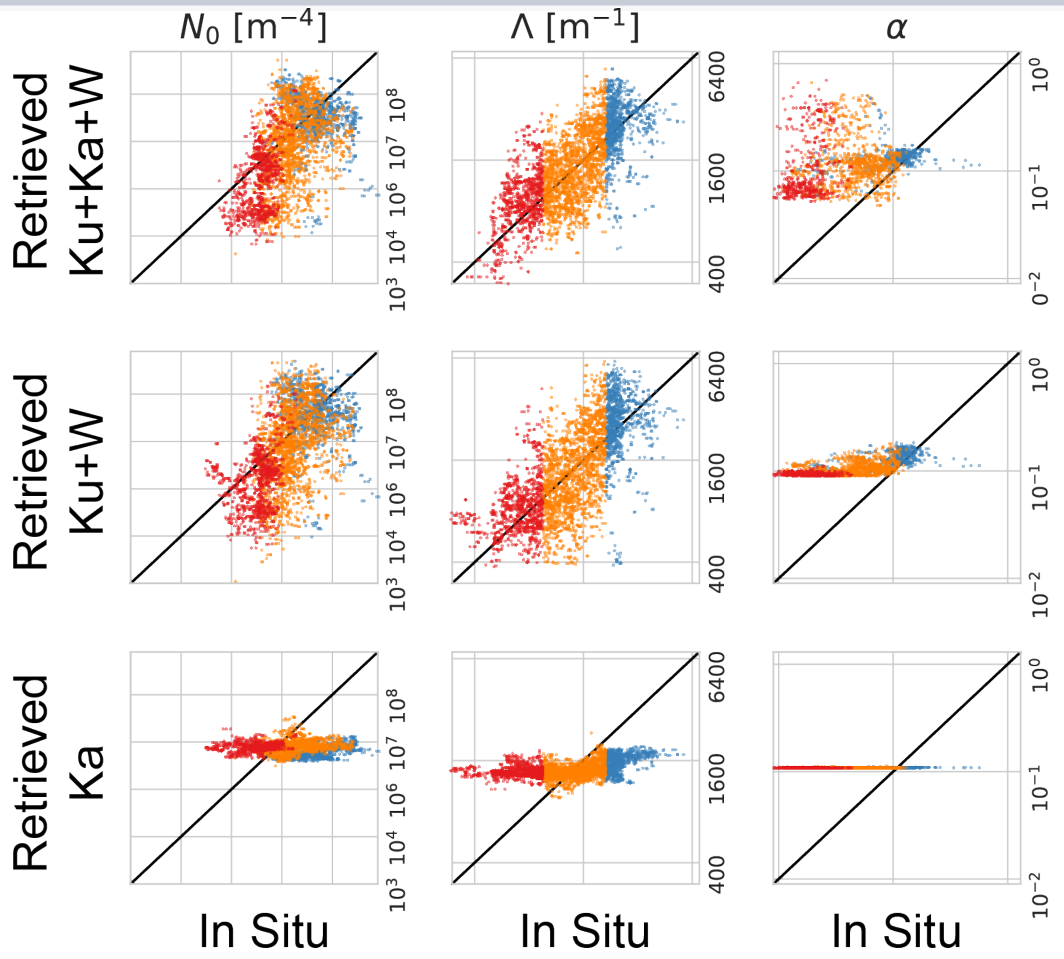
Use of Field Campaign Data in Retrieval OSSEs

- A key component of the DS study is the use of existing field campaign data
- When combined with a Bayesian retrieval framework, field measurements can be used in an OSSE context
- Example: "data denial" retrieval study from OLYMPEX (Leinonen et al. 2018; JAOT)
- Retrieve parameters of snow PSD using 1, 2, or 3 radar frequencies (APR-3: W, Ka, Ku)
- Compare vs. in situ data (2D-S Probe, UND Citation)



In situ vs retrieved snow PSD parameters from 3, 2, and 1 radar frequencies. Adapted from Fig. 3, Leinonen et al. 2018 (JAOT)

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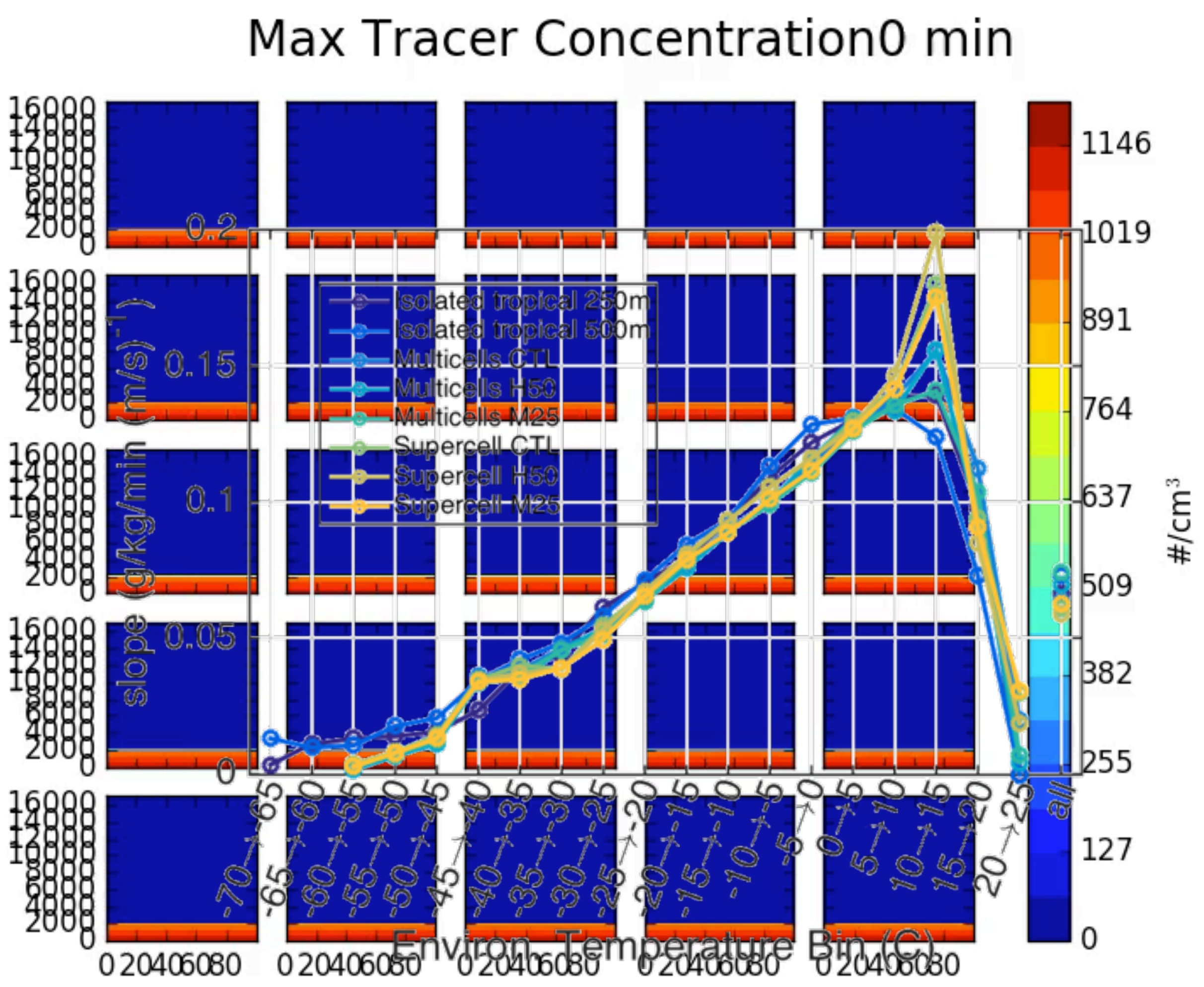
Process OSSE

- Assessment of whether a measurement captures a *process* is challenging
- E.g.: ”determine convective transport and redistribution of mass, moisture, momentum, and chemical species”
- Requires:
  - Identify process of interest
  - Establish uncertainty bounds on the process
  - Connect (quantitatively) measurement with process
- This is an area of research, but early results indicate ensembles of simulations can be used to quantify capability



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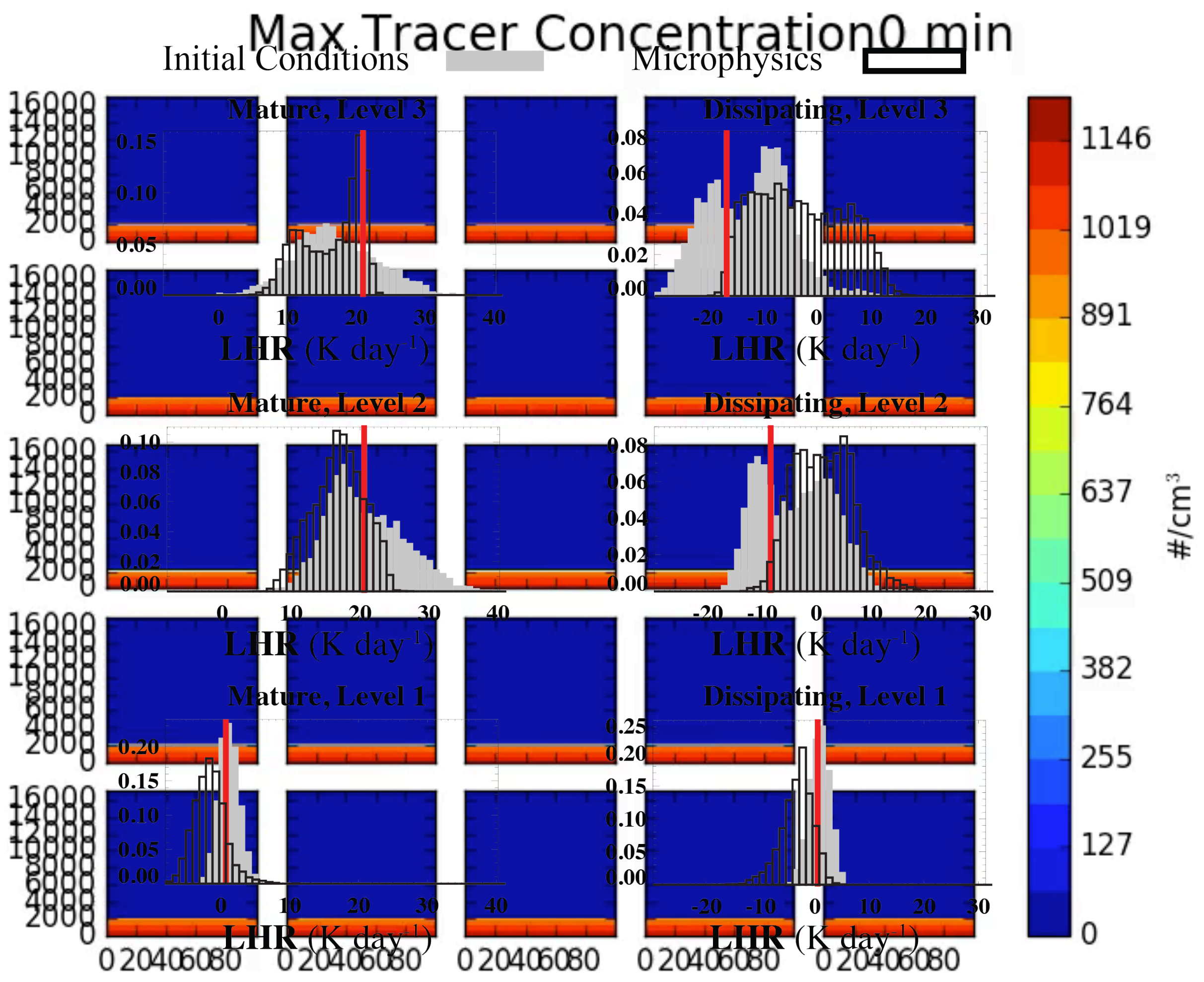

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Cloud-Scale All-Sky Data Assimilation

(Courtesy Masashi Minamide, masashi.minamide@jpl.nasa.gov)

- Cloud-scale all-sky DA is challenging due to *representativeness*

If… Observation  Forecast  or Observation  Forecast  then obs increment can be very large

- Consider an update to sea level pressure given obs of brightness temp

SLP update will be $$\left(\frac{\sigma_{f,y}\sigma_{f,x}corr(x,y)}{\sigma_{f,y}^2+\sigma_o^2}\right)\Delta y = \frac{5\times 5\times 0.5}{5^2+3^2}\times 40K\sim \quad \mathbf{15\mathit{hPa}}$$

- Need to deal with obs-forecast mismatch

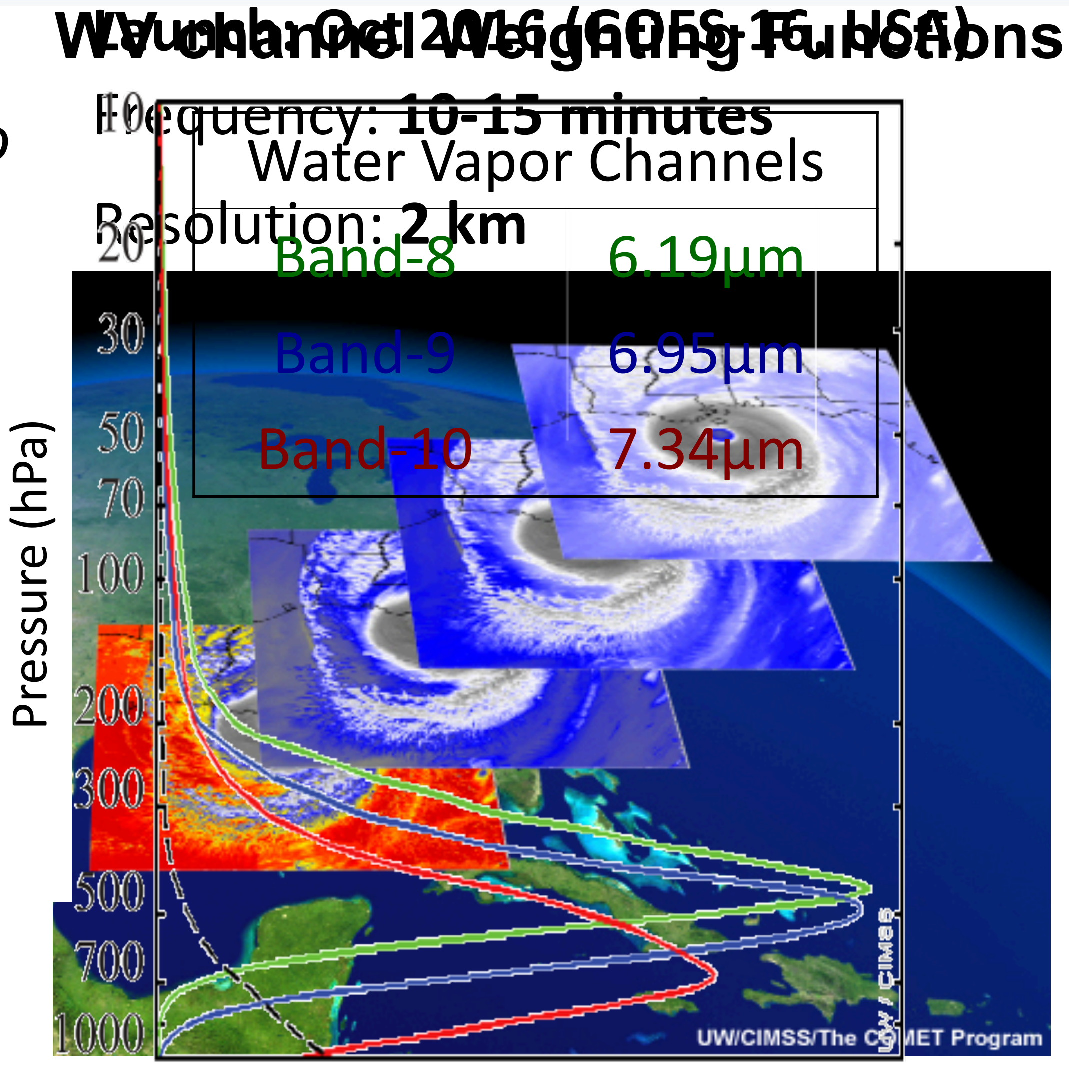
Inflate Background Error (ABEI)

Inflate Observation Error (AOEI)

Forecast/Analysis OSSE

(Results courtesy Masashi Minamide, masashi.minamide@jpl.nasa.gov)

- Applications may or may not explicitly include forecasting, but *data assimilation can be used to assess measurement information*
- Measurement effect on the *analysis* – the state estimate produced by data assimilation
- Assimilate new data alongside current data - allows assessment of information *in context*
- Example: assimilation of GOES-16 brightness temperatures
  - WRF model with 3 km grid spacing on inner domain
  - Use Ensemble Kalman Filter DA with 60 members
  - Account for representativeness using AOEI and ABEI



(*Otkin* 2012)

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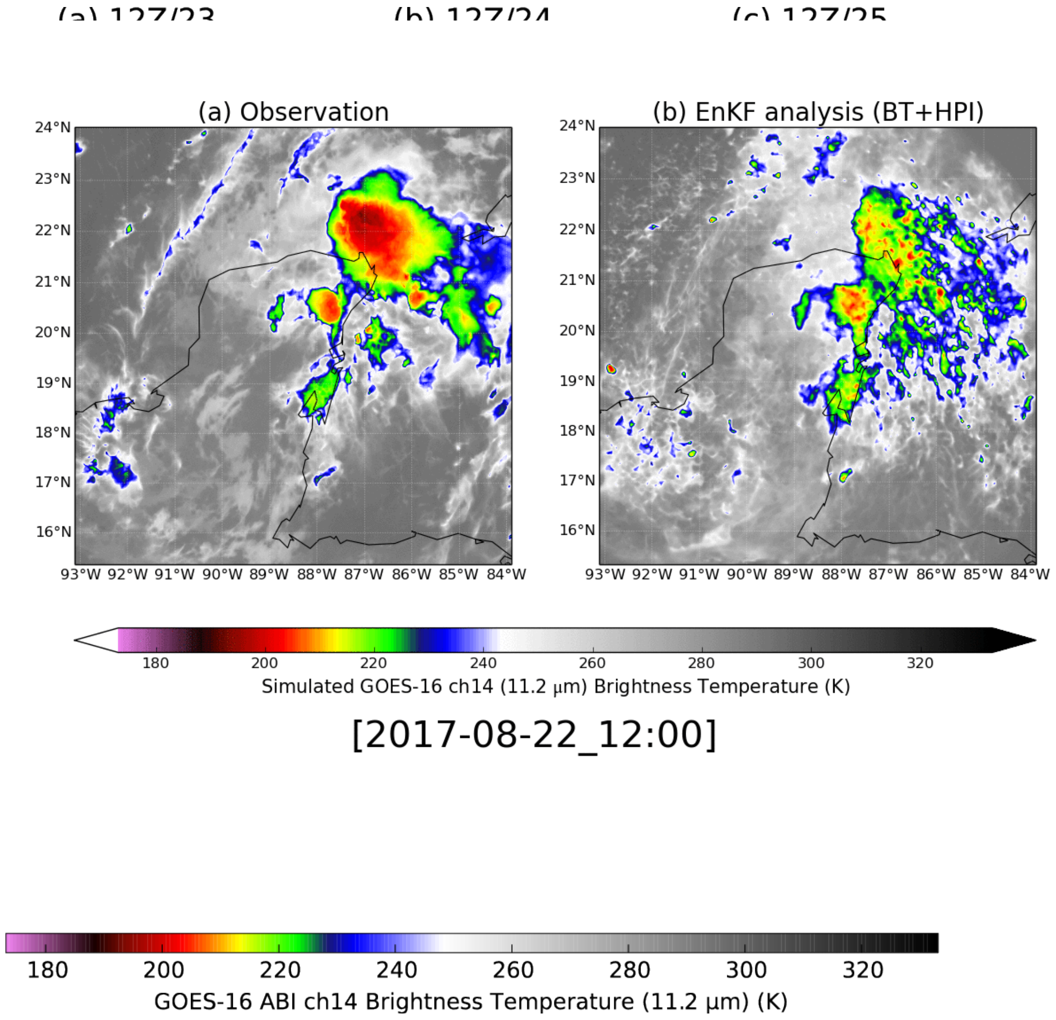

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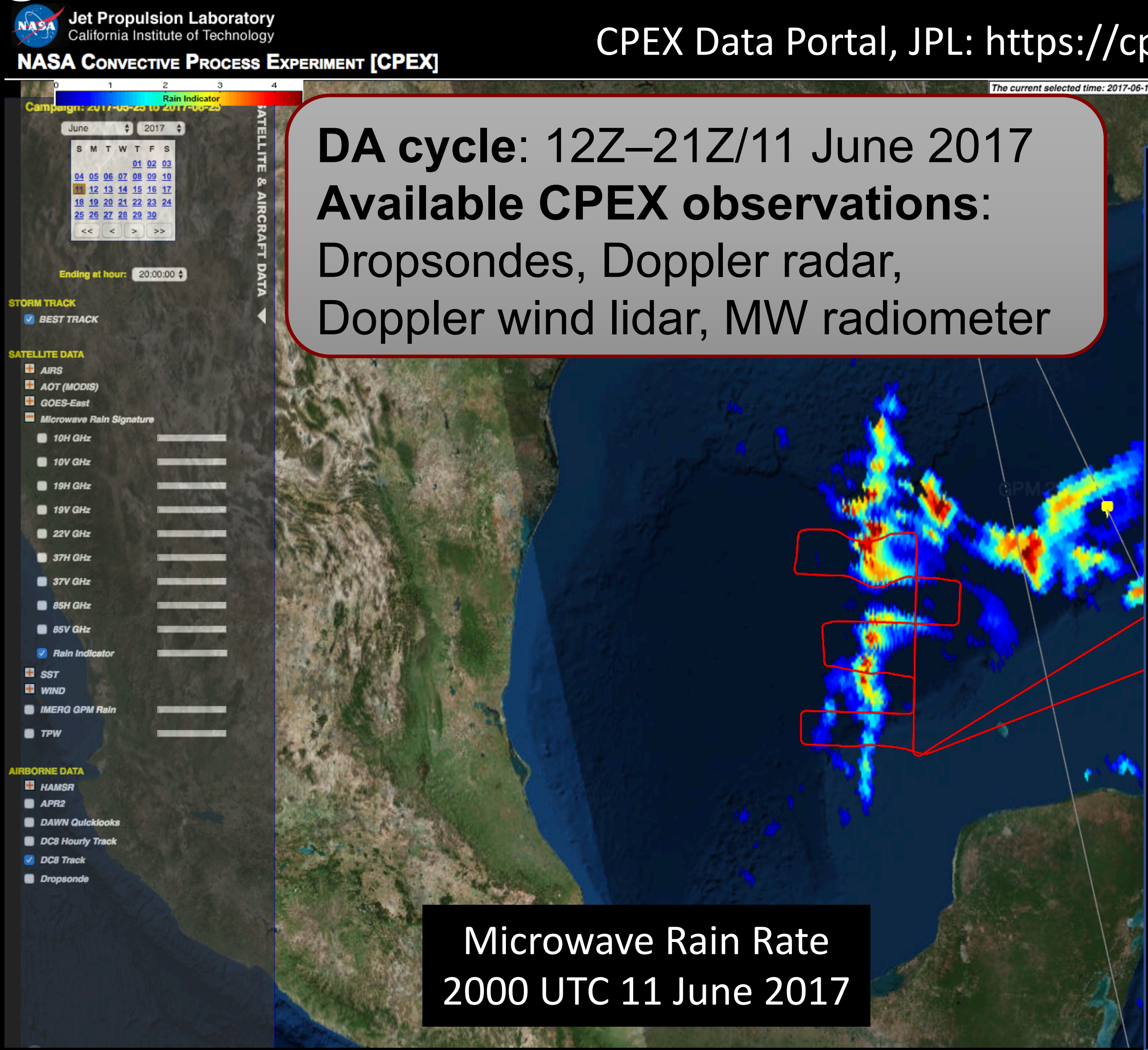
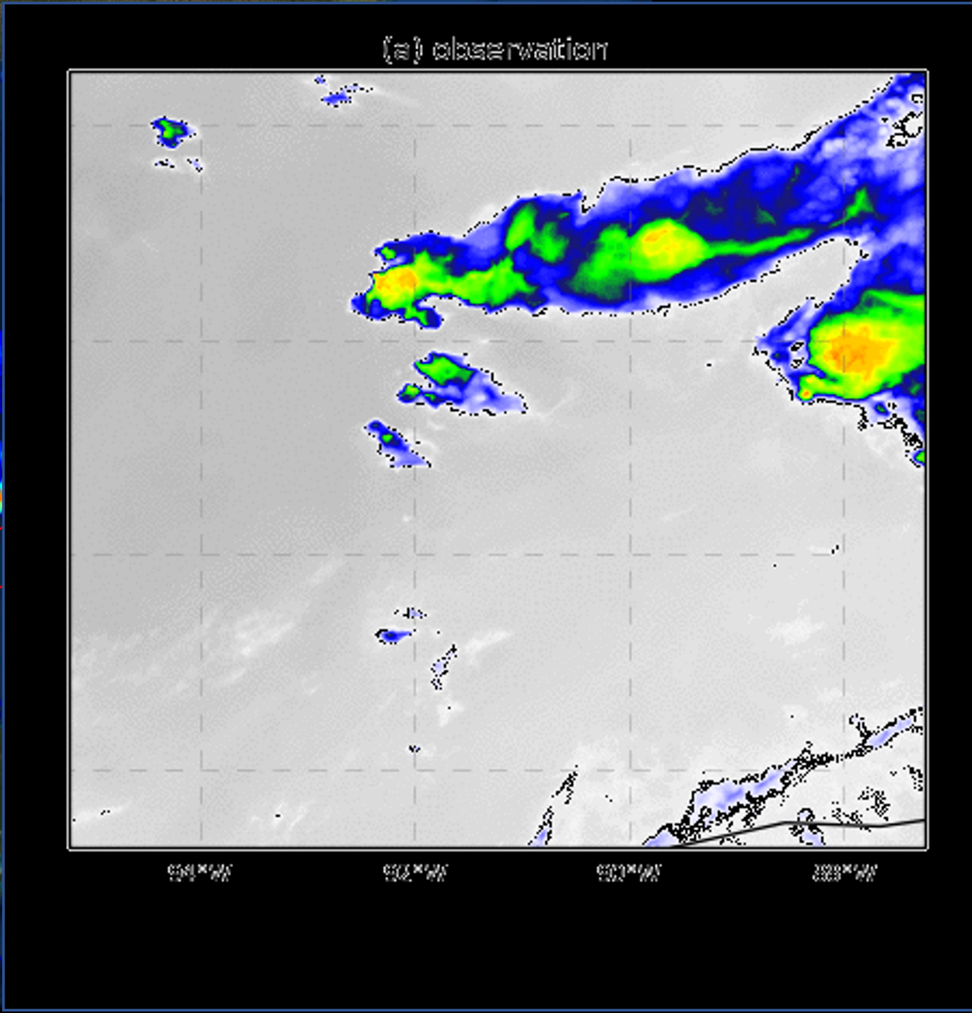
Unorganized Convection: 06/11/2017 during CPEX

CPEX Data Portal, JPL: https://cpexportal.jpl.nasa.gov



DA cycle: 12Z–21Z/11 June 2017
Available CPEX observations:
Dropsondes, Doppler radar,
Doppler wind lidar, MW radiometer

Microwave Rain Rate
2000 UTC 11 June 2017



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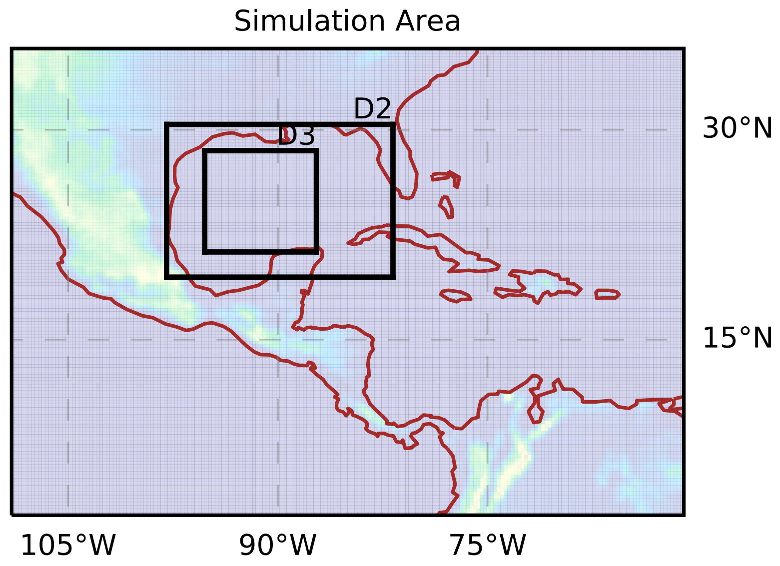
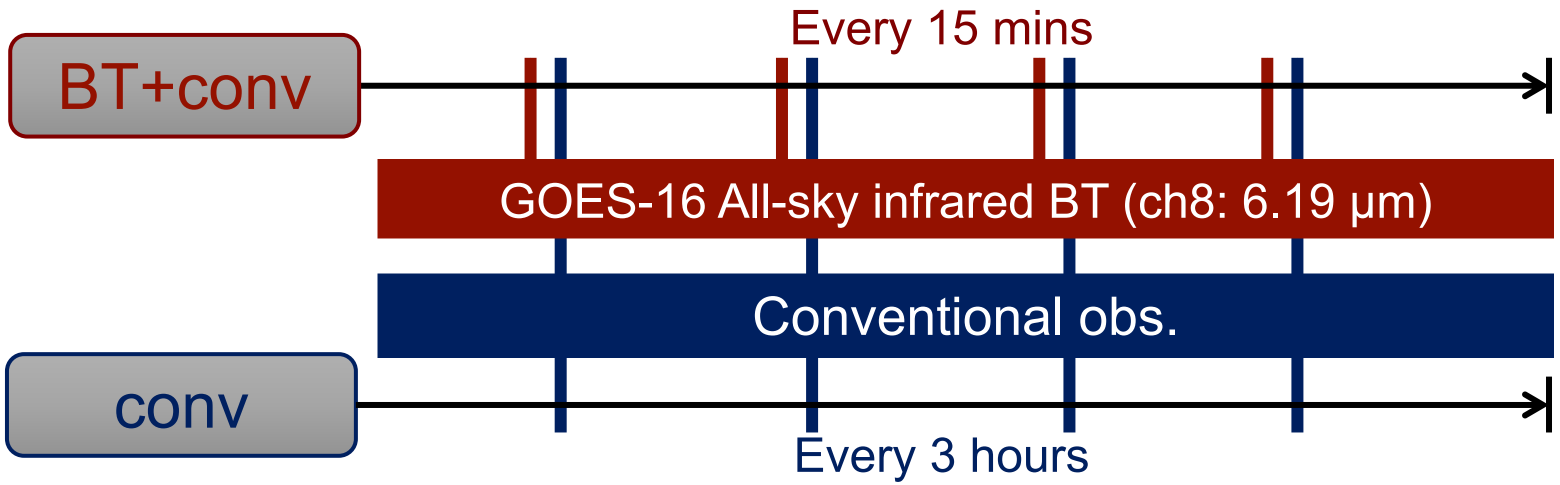
Model Configuration and Experiment Settings

- WRF ver.3.6.1, CRTM, PSU WRF-EnKF (APSU) DA
- 27/9/3 km grid, 60 member ensemble (EnKF on domain 3)
- Assimilate conventional obs every 3 hours, GOES-16 channel 8 every 15 min
- Error modeling, inflation, and localization
  - Adaptive Observation Error Inflation (AOEI) (Minamide & Zhang, 2017, MWR)
  - Adaptive Background Error Inflation (ABEI) (Minamide & Zhang, 2019, QJRMS)
  - Successive covariance localization:
    - 18 km thinning with 200 km localization radius
    - 12 km thinning with 30 km localization radius
  - 3K brightness T errors





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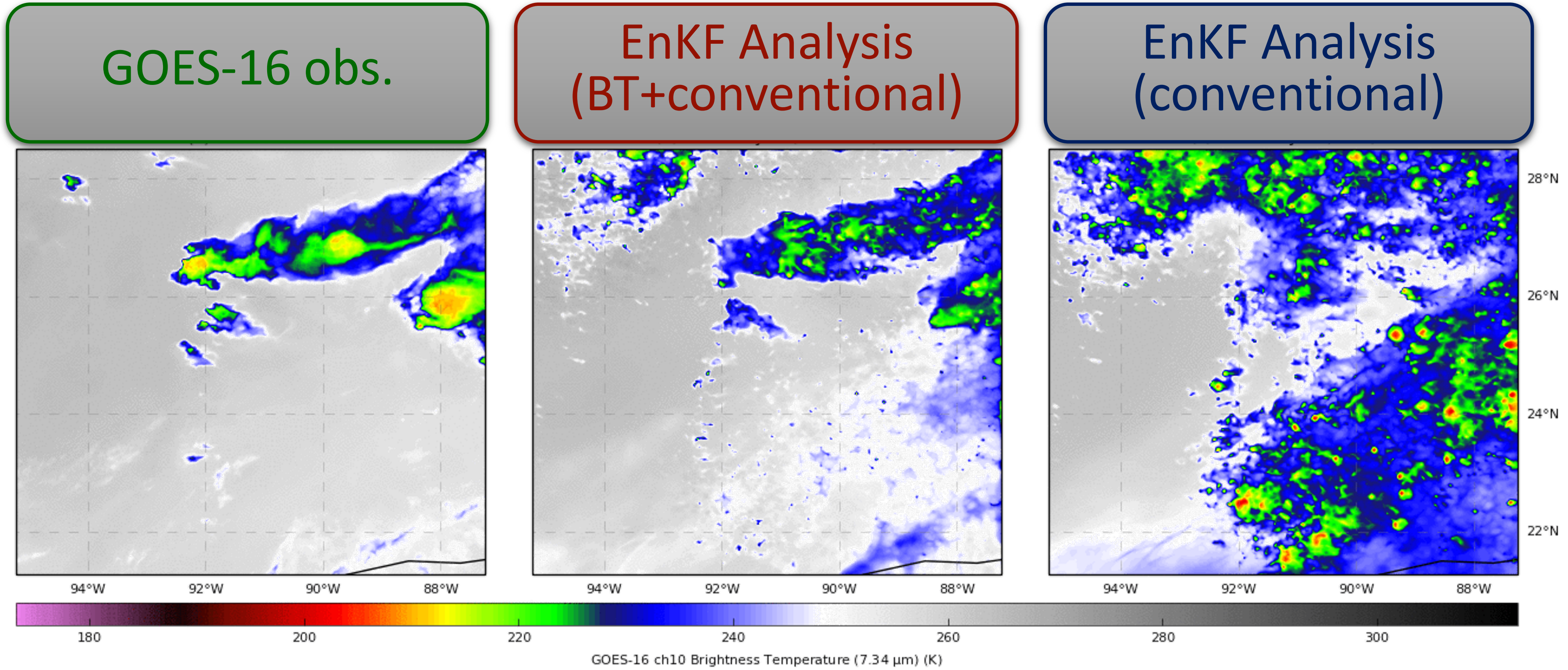
EnKF Performance (Analysis)

(Results courtesy Masashi Minamide, masashi.minamide@jpl.nasa.gov)



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Assimilation of GOES-16 brightness temperature (with Adaptive Observation & Background Error Inflation (AOEI and ABEI) methods) worked well in constraining the convective activity during CPEX

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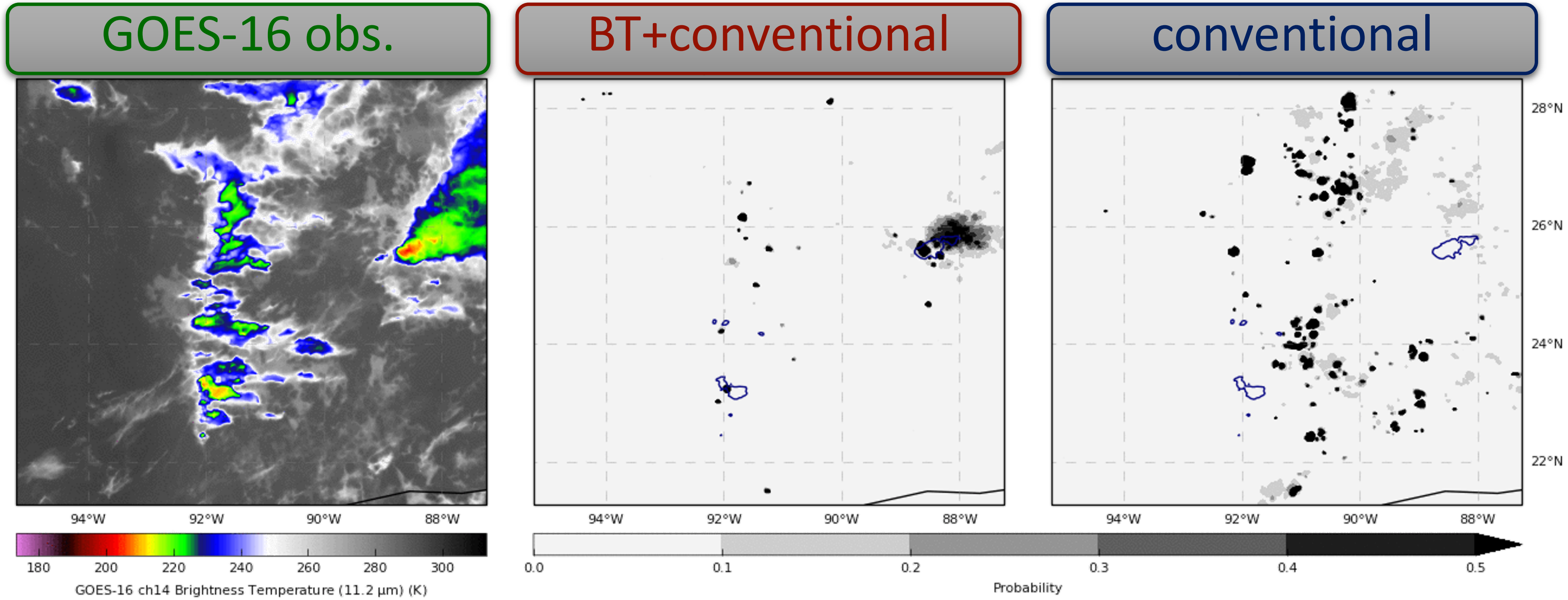
EnKF Performance (Probabilistic Forecast)

(Results courtesy Masashi Minamide, masashi.minamide@jpl.nasa.gov)

20 Ensemble probabilistic forecast of Tb < 215 K
Initialized at 15Z/11 June 2017 (after 3-hours of assimilation)



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Although shifted eastward, assimilation of all-sky BTs helped to better constrain the occurrence of newly developing convection.

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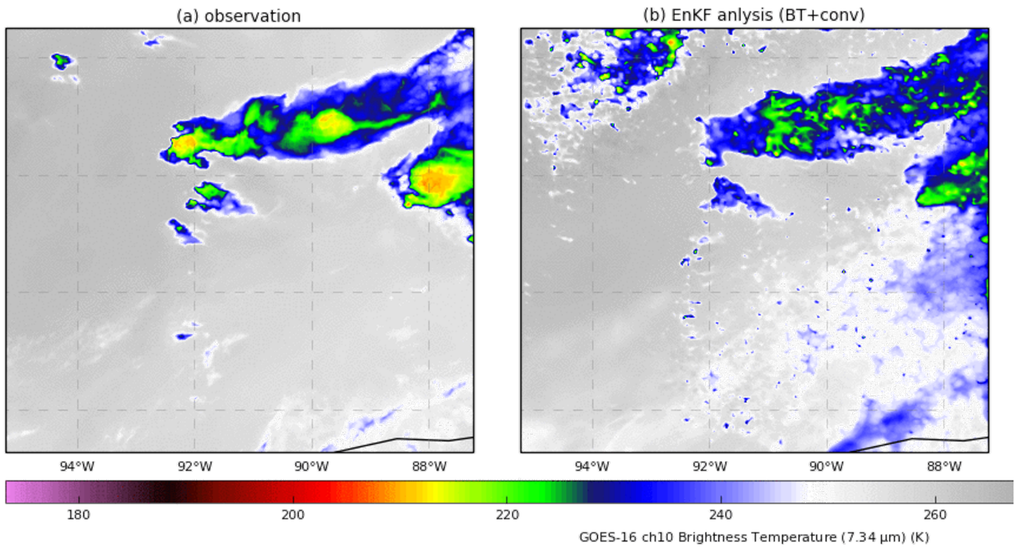
Next Step: Convective Dynamics

- CPEX and Harvey DA results look very realistic, but… are they?
- Cloud top brightness temperatures are connected to unorganized deep convective updrafts, but only indirectly.
- Questions:
  - What constraint did the GOES-16 observations place on convective dynamics?
  - Which additional observations may be necessary to constrain convective vertical mass flux?



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- Next steps:
  - Mine ensemble to explore constraint of GOES-16
  - Simulate other observations and assess their impact (probilistically)

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OSSE Spectrum: Summary and Caveats

- Adequate sampling and resolution is the low bar
- Next step is geophysical parameter uncertainty assessment
- Both are pre-requisites for process and/or forecast OSSEs
- Uncertainty can be quantified, but results should be qualified…
  - Outcomes of any OSSE depend on
    - Representation of “nature”
    - Representation of uncertainty in measurements and forward models
  - Caution - by the time of launch/data acquisition:
    - Retrieval framework may (will) be different
    - Program of record may (will) be different
    - Forecast/DA systems may (will) be different

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Putting it all together:
A Notional End to End OSSE for Convective Dynamics

Targeted Observable: Convection and Cloud Dynamics (DS TO-5)

Science Objective: measure vertical motion in deep convective cloud systems

- Sampling:
  - GMAO nature run + convective system feature identification: determine orbit period, swath, single vs multiple observatory, etc
  - Use database of high resolution CRM simulations to explore effect of changes in footprint size, instrument sensitivity, and swath width (consequences of partial observation of updrafts)
- Retrieval:
  - Apply instrument simulator to CRM database
  - Retrieve vertical motion, compare uncertainty vs desired capability
- Process:
  - Vary controls on convective dynamics in a CRM ensemble
  - Use synthetic dynamics retrieval to assess information on convective processes
- Analysis:
  - Use a convective scale ensemble as a baseline
  - Assimilate GOES-16 (and other PoR data)
  - Simulate measurements from one member, and assimilate them in the EnKF system to assess addition of information relative to PoR

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Backup Slides

OSSEs for CCP: Tools and Algorithms

Leverage available resources

1. Instrument simulators with (nonlinear) Bayesian retrieval algorithms
   - Allow robust estimates of information content and observability
   - Produce quantitative assessments of retrieval uncertainty
   - Accommodate multiple possible instrument types (including program of record)
2. High resolution simulations of clouds, convection, and precipitation coupled with instrument simulators
   - Large ensembles (100s of members) have already been generated for convection of multiple types and in multiple regions at 250 m grid spacing
   - Ensembles (10s of members) also generated for extratropical cyclones at 1.33 km grid spacing
   - The GEOS-5 Nature Run, while not convection resolving, can be used for coarse-grained sampling studies
3. Ensemble-based data assimilation systems at convection resolving scales
   - Ensembles naturally accommodate process nonlinearity and representativeness
   - Recent work has demonstrated effective assimilation of PoR – experiments can be expanded to include potential future observations

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OSSEs for CCP: Study Team

- Science Impacts Team
  - Univ. Utah (J. Mace, Z Xu)
  - GSFC (J. Munchak, M. Grecu, I. Adams)
  - JPL (D. Posselt, M. Lebsock, M. Minamide, E. Nelson, R. Storer)
  - MSFC (W. Peterson, D. Cecil, P. Gatlin, T. Lang)
- Conduct OSSEs for CCP, which involve any of the elements of the spectrum deemed necessary to provide information to the architecture study
- Note that many studies have already been conducted and “expert elicitation” is a valid source of information

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All-sky satellite radiance DA

New assimilation techniques for all-sky DA

Adaptive observation error inflation (AOEI)

- **Minamide, M.**, and F. Zhang, 2017: Adaptive Observation Error Inflation for Assimilating All-sky Satellite Radiance, *MWR*, 145,1063-1081

Adaptive background error inflation (ABEI)

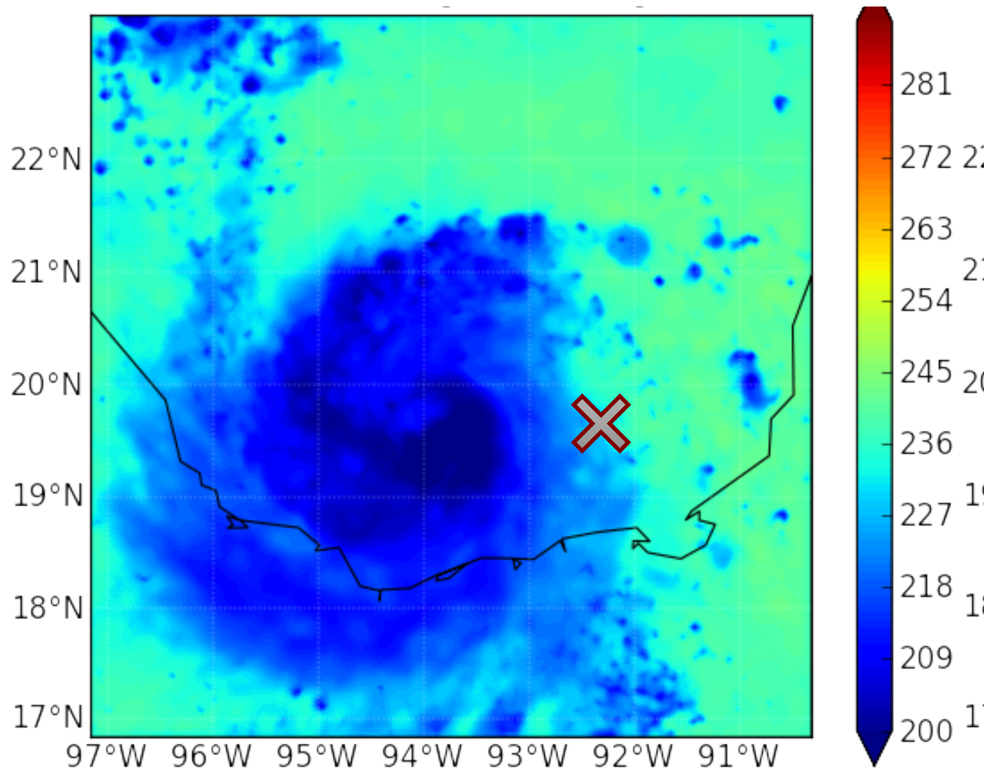
- **Minamide, M.**, F. Zhang, 2019: An Adaptive Background Error Inflation Method for Assimilating All-sky Radiances, *QJRMS,* doi:10.1002/qj.3466.

Application to TC prediction

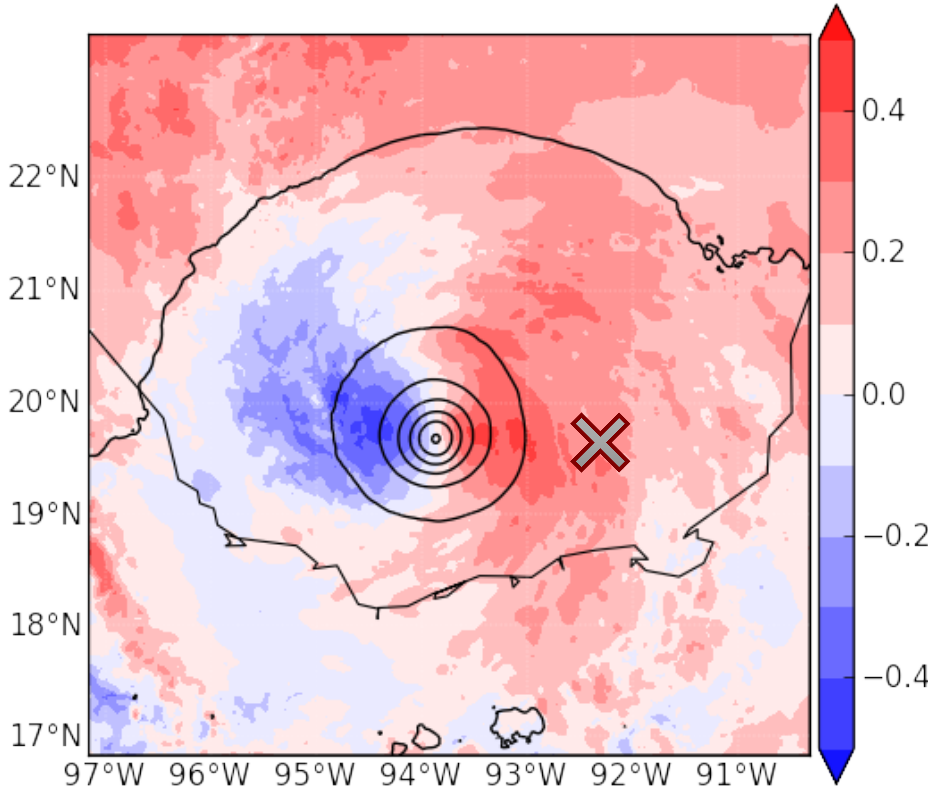
Real-data application on GOES-16 ABI:

- ***Minamide, M.**, F. Zhang, E.E. Clothiaux, 2018:* Dynamics and Predictability of Hurricane Harvey (2017) Examined through Convection-permitting Ensemble Assimilation of All-sky GOES-16 Radiances, in prep for the submission
- Zhang, F., **M. Minamide**, X. Chen, R. G. Nystrom, S.-J. Lin and L. M. Harris, 2018: Improving Harvey forecasts with next-generation weather satellites, *BAMS IN-BOX*

Potential impacts of assimilating BTs



Simulated GOES-R ABI Ch8 (6.19 µm) brightness temperature

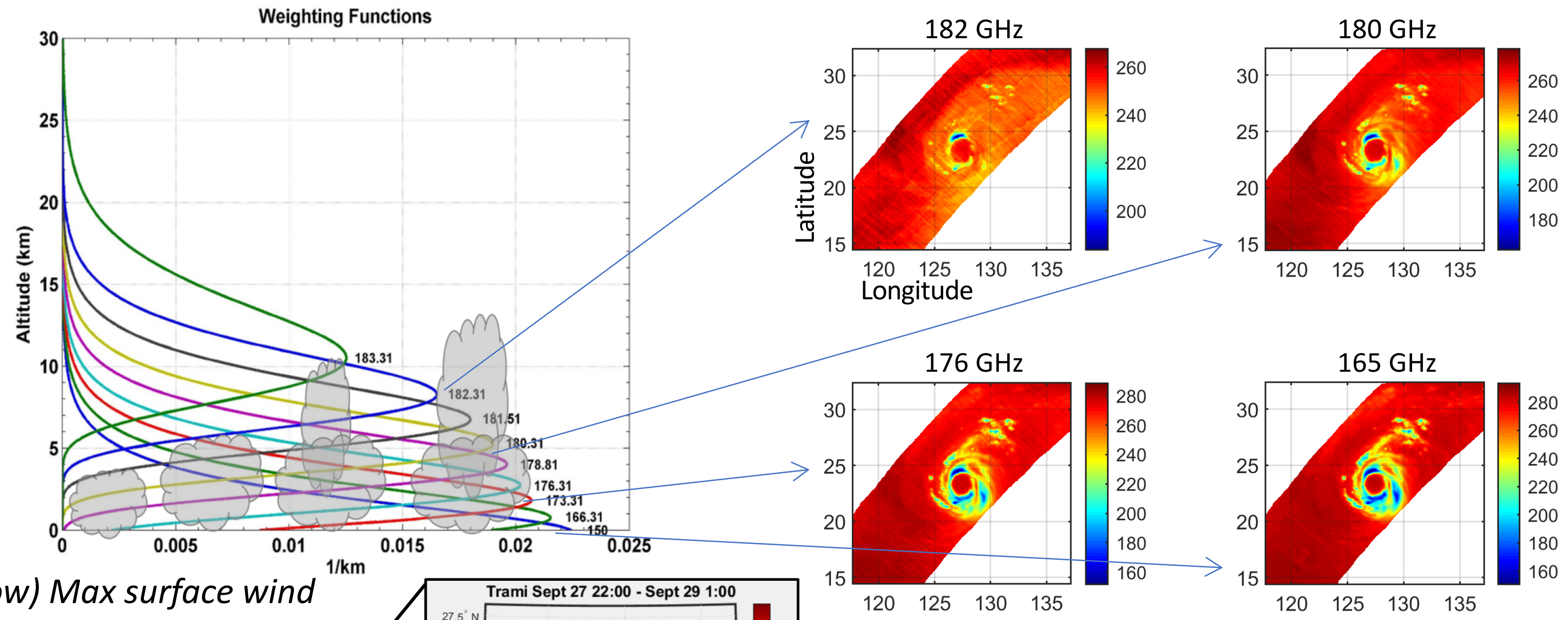


Colors: ensemble correlation of SLP to brightness temp. at 'X'

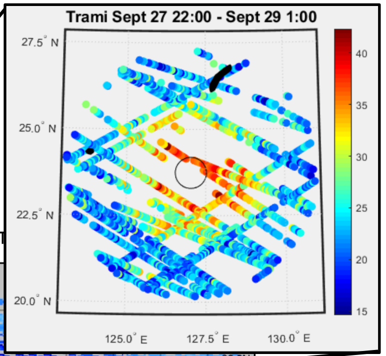
Contours: ensemble mean SLP

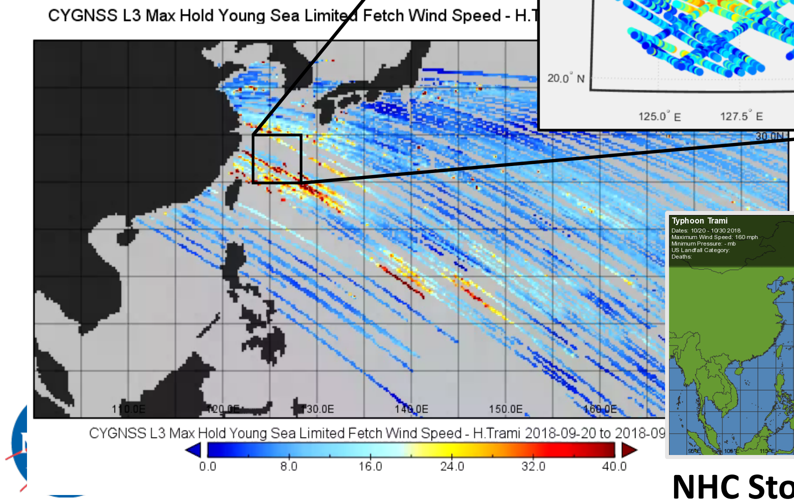
(Zhang, Minamide and Clothiaux, 2016, *GRL*)

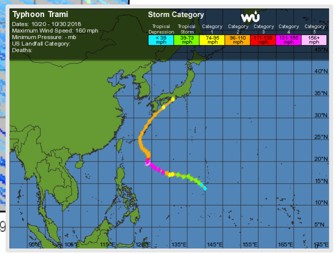
Exploring Synergy Among Small-Sats: Typhoon Trami



(below) Max surface wind throughout Trami lifecycle; (insert) Storm-centric composite wind tracks latent heat flux

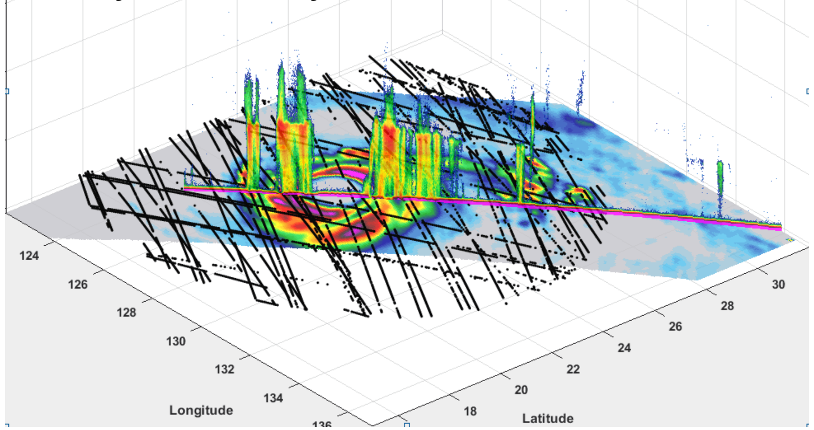






NHC Storm Track

Similar asymmetry observed in depth of eyewall convection between TEMPEST-D and RainCube (strongest on west side and to the south). CYGNSS winds in inner core provide estimate of latent heat flux.



Future: exploit synergy among measurements to capture process-level interactions in TCs

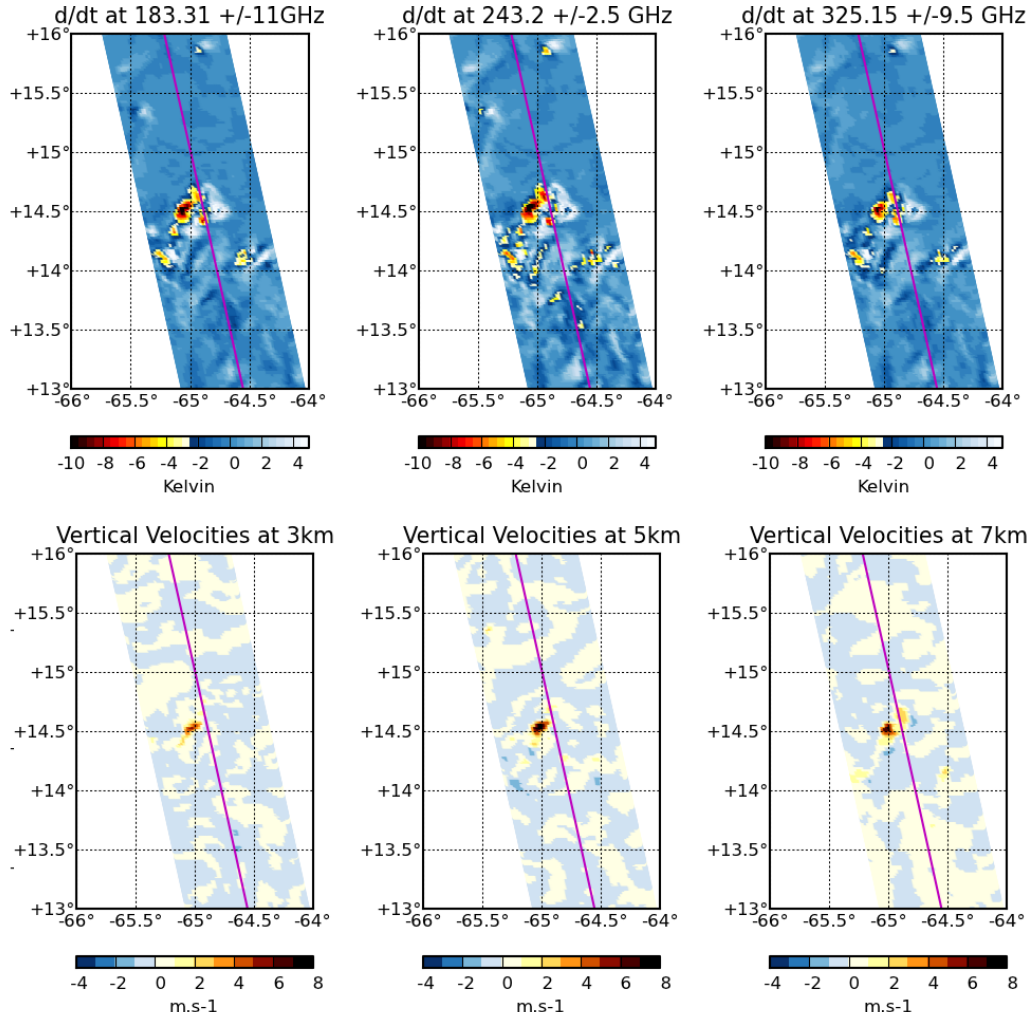
Combination of CYGNSS, TEMPEST-D, and RainCube for Typhoon Trami

- Surface Latent Heat Flux (CYGNSS)
- Spatial Cloud/Precip Context (TEMPEST-D)
- Cloud Vertical Structure (RainCube)

Future advance: rapid revisit?

Retrieval OSSE: Temporal Sampling

- Recent simulation results using a cloud resolving model and microwave brightness temperature simulator
- Close correspondence between brightness temperature difference and vertical velocity
- Results courtesy Philippe Chambon (MeteoFrance) via Ziad Haddad



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