Quantifying Tropopause-Overshooting Volume from Satellite and Radar Observations During the DCOTSS 2021 and 2022 Campaigns

Kristopher Bedka[1], Kyle Itterly[2], Cameron Homeyer[3], and Konstantin Khlopenkov[2]

[1] Science Directorate, NASA Langley Research Center
[2] Analytical Mechanics Associates
[3] School of Meteorology, University of Oklahoma

Contact: kyle.f.itterly@nasa.gov and kristopher.m.bedka@nasa.gov

Image Caption: ISS Photo of overshooting convection over Mississippi, 09/06/2021: https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS065&roll=E&frame=357924

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

Motivation

- **Among many other questions, the Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) Mission sought to answer:**
  How much tropospheric air and water is irreversibly injected into the stratosphere by convection?

- **The volume of stratospheric convective injection can be quantified at the individual storm cell scale from:**

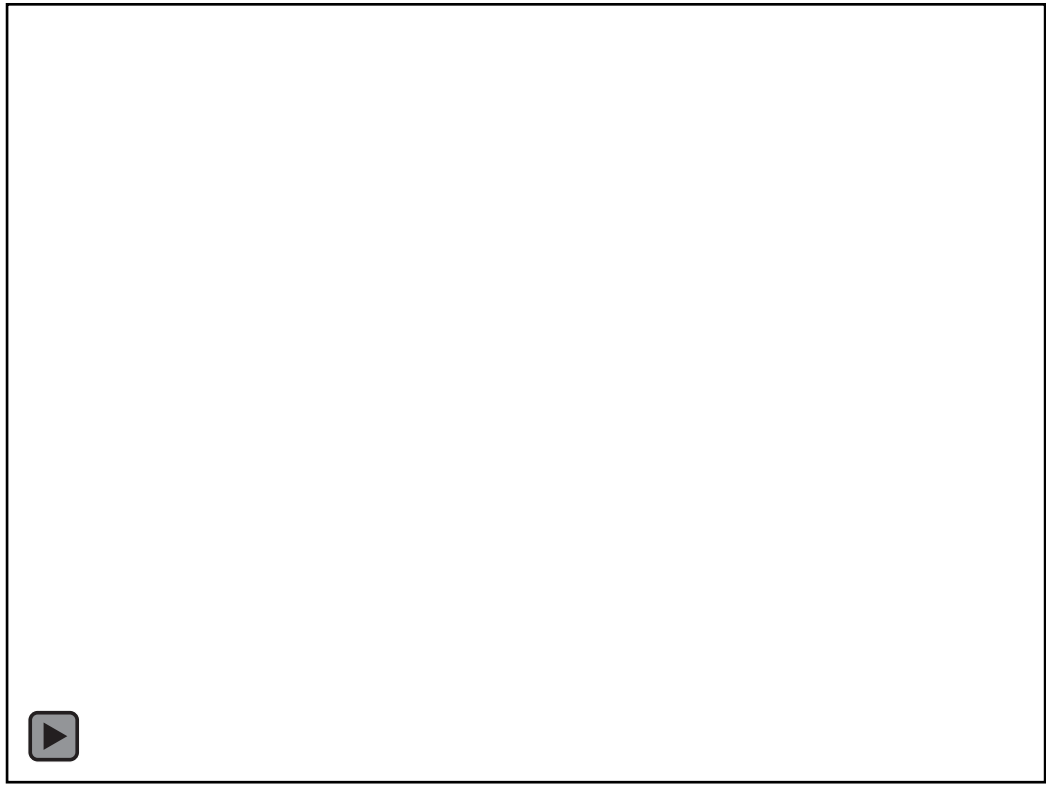
1) Radar precipitation echo top height (e.g. Jellis et al. 2023)
2) Geostationary (GEO) satellite-derived overshooting top detection and cloud height retrieval (e.g. Khlopenkov/Cooney et al. 2021)

- **It is quite challenging to quantify cell-scale injection from a GEO satellite perspective because individuall “cells” are ill-defined and hard to track, and their anvils merge**

- **Organized groups of convective cells (“storm outbreaks”) significantly impact the stratospheric moisture budget**

- **Anvils from storm outbreaks can be tracked from many hours from initial development to decay, allowing us to quantify convective injection from organized convective storm events with persistent and widespread overshooting**

GOES-16 Color-Enhanced IR Temperature Imagery of Several Consecutive Convective Outbreaks: 28-30 April 2017



https://www.goes-r.gov/multimedia/originalVideoCopies/dataAndImagery/GOES16/28-30apr17_band13.mp4

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

Goals of This Study

- **We developed a novel method for defining individual storms, or cluster of adjacent storms, as objects and tracking them throughout their lifetime using GOES-16/17 satellite data during DCOTSS 2021 and 2022 airborne field deployment study periods**

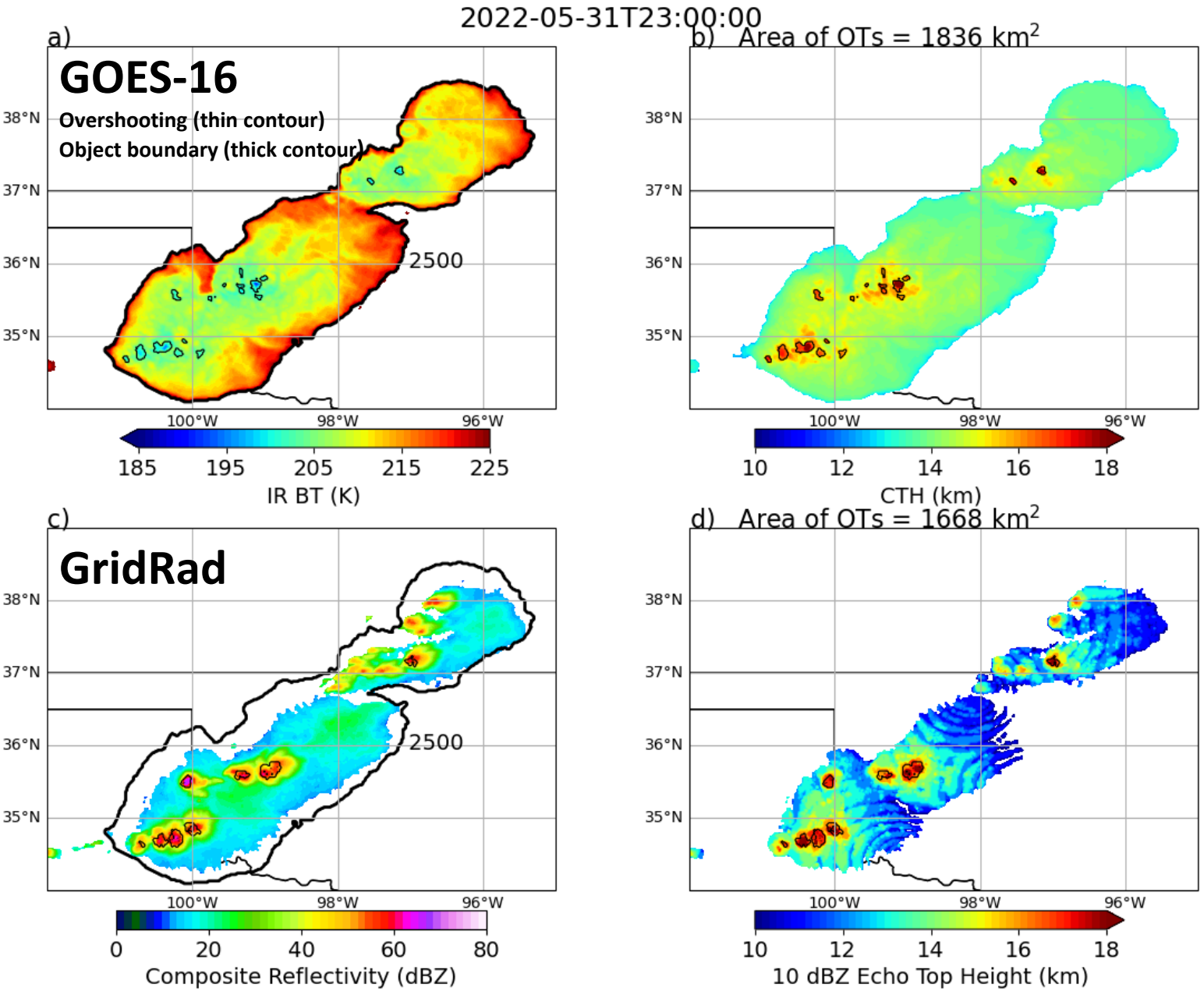
- **We combine this object tracking method with GOES and NEXRAD depictions of overshooting to:**
  1. Quantify the fractional area within an anvil cloud where overshooting occurs
  2. Quantify and compare overshooting area and volume derived from NEXRAD and GOES
  3. Quantify injection volume from extreme convective storm outbreaks
  4. Assign overshooting parcel trajectories within storm objects to demonstrate the areal extent of convectively-influenced stratospheric air masses

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

Data and Methods

- **MERRA-2 Tropopause Temperature – GOES-16 IR temperature difference used to define storm objects**
  - Pixels up to 20 K warmer than tropopause (MERRA-2 blended lapse-rate and PV) define anvil extent at 10 min intervals
  - Study Periods: 5 July – 24 August 2021, 12 May – 13 July 2022. Domain: 12-52° N, 66-125° W
- **Objects tracked with tracking and object-based analysis of clouds (tobac) open-source Python package**
  - tobac has a variety of settings to define how objects are defined and tracked, which were experimented with extensively to generate the most stable/accurate tracks. Learn more about tobac here: https://tobac.readthedocs.io/en/latest/
  - Minimum object area = 1000 GOES 2 km IR pixels (66x66 km anvil if it were square)
  - Watershed segmentation applied at feature centroids to fill object bounds
  - Objects tracked in time, using several frames in memory and centroid distance threshold. Object merging/splitting also handled
- **NEXRAD overshooting volume derived where GridRad overshooting criteria are satisfied**
  - Criteria: 10 dBZ echo top >= 0.5 km above tropopause, with ≥ 20 dBZ column, 2 km grid and 10 min intervals
  - See Homeyer and Bowman (2023) for GridRad description: https://gridrad.org/pdf/GridRad-v4.2-Algorithm-Description.pdf
- **GOES overshooting volume based on detection of cold pixel cores considered to be overshooting tops (OTs)**
  - GOES OT probability >= 0.5 at the 2 km GOES grid used to define overshooting: Khlopenkov et al., Cooney et al. (JGR, 2021)
  - 0.5 km overshooting depth corresponds to ~1.6 K temperature differential between OT and tropopause in the DCOTSS cloud top height product
- **GOES and GridRad DCOTSS datasets available online at: https://www-air.larc.nasa.gov/missions/dcotss/index.html**

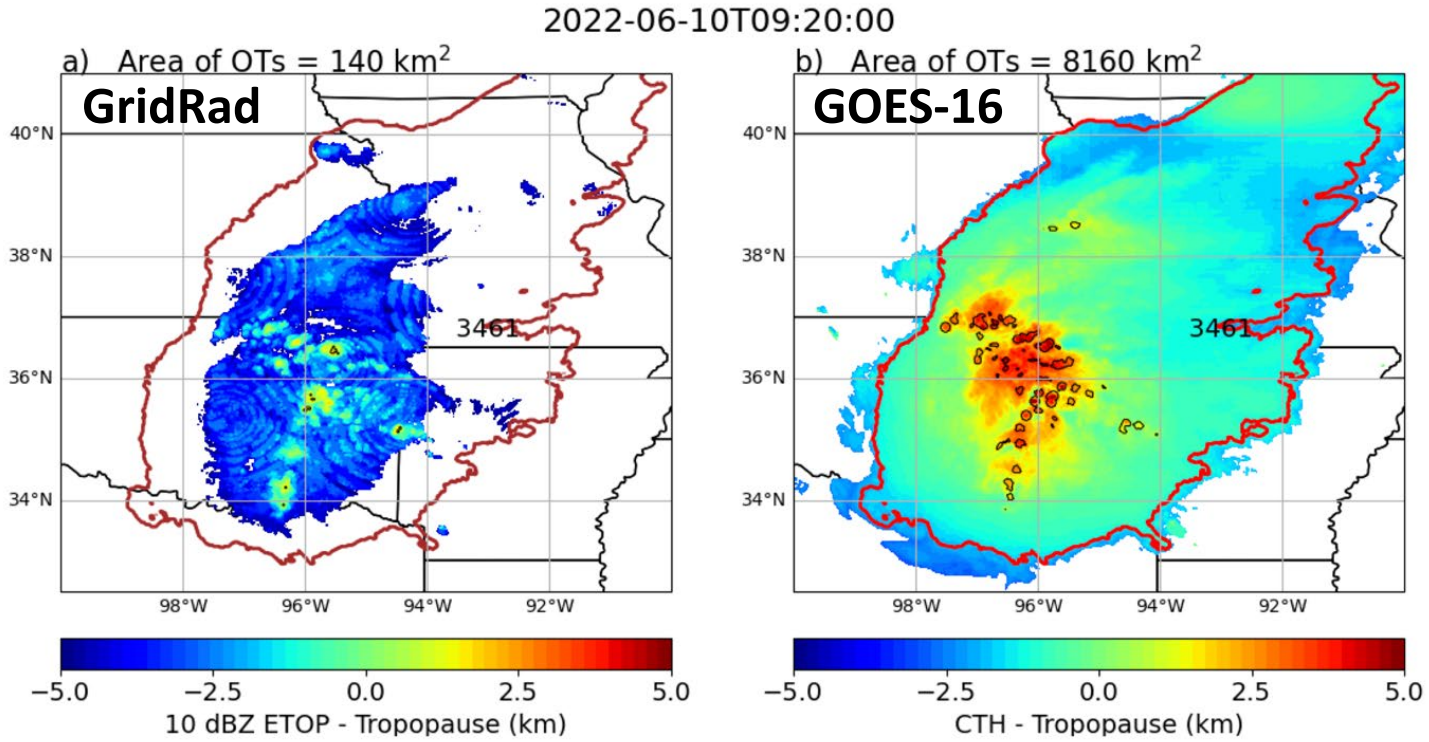
How Do GOES and GridRad Depict Overshooting?

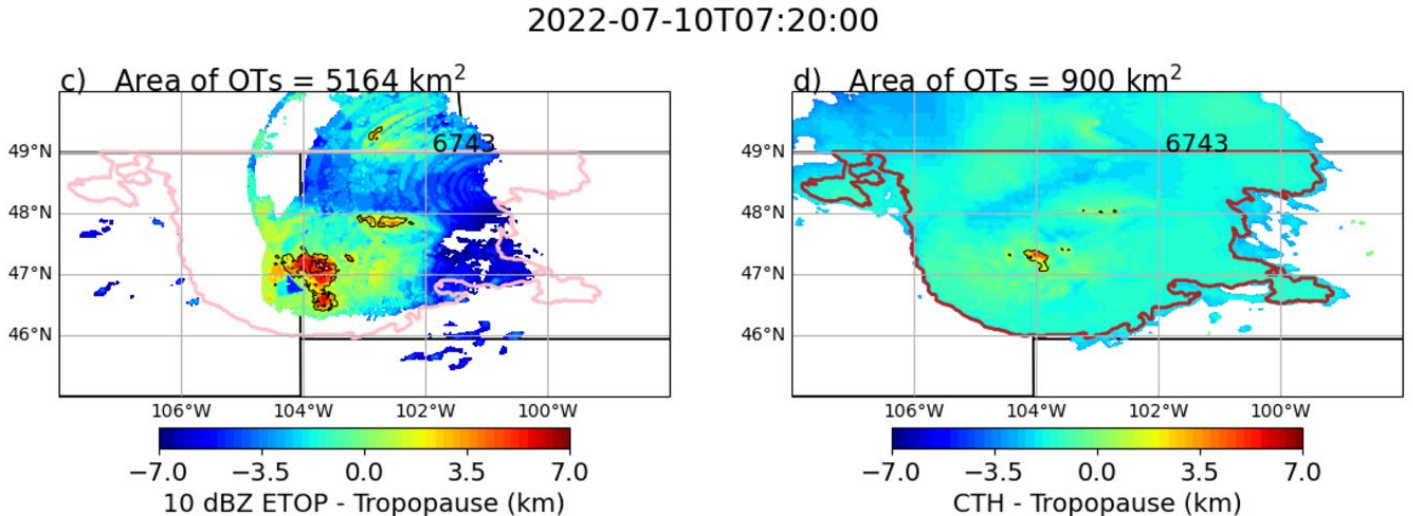


- 31 May – 1 June 2022 was one of the best active convection sampling cases during the DCOTSS mission (see Gordon et al. ACP, 2023)
- GridRad depicts more extreme heights and larger convective cores in this example
- GOES overshooting regions capture the same OTs as GridRad but also some adjacent cold outflow, where temperatures from very recent overshooting remain colder than the tropopause

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

How Do GOES and GridRad Depict Overshooting?





- These two examples show scenes with notable disagreement between GOES and GridRad depictions of overshooting
- The top example shows a broad area of cold cloud with height ≥ 2 km above the tropopause
- Many localized areas with cold temperature that ”look like” OTs from a GOES perspective are detected. Fewer/smaller OTs detected by GridRad
- The bottom example over Montana/North Dakota shows very deep penetration from GridRad, not nearly as significant from GOES
- This region is far from GOES nadir, and has poor NEXRAD coverage, leading to uncertainties with both sensor’s depictions of overshooting
- GOES is typically more aggressive with OT area, while not being quite as as deep as GridRad
- Uncertainties in OT area and depth impact overshoot volume statistics

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

Storm Outbreak Object Tracking Example



Storms initiated in the Texas Panhandle and Oklahoma, and spread northeastward as the outbreak evolved

The anvils from neighboring storms merged into one giant cold cloud region (object ID# 2500) from Texas to Illinois, which was tracked for a 17.7 hour period

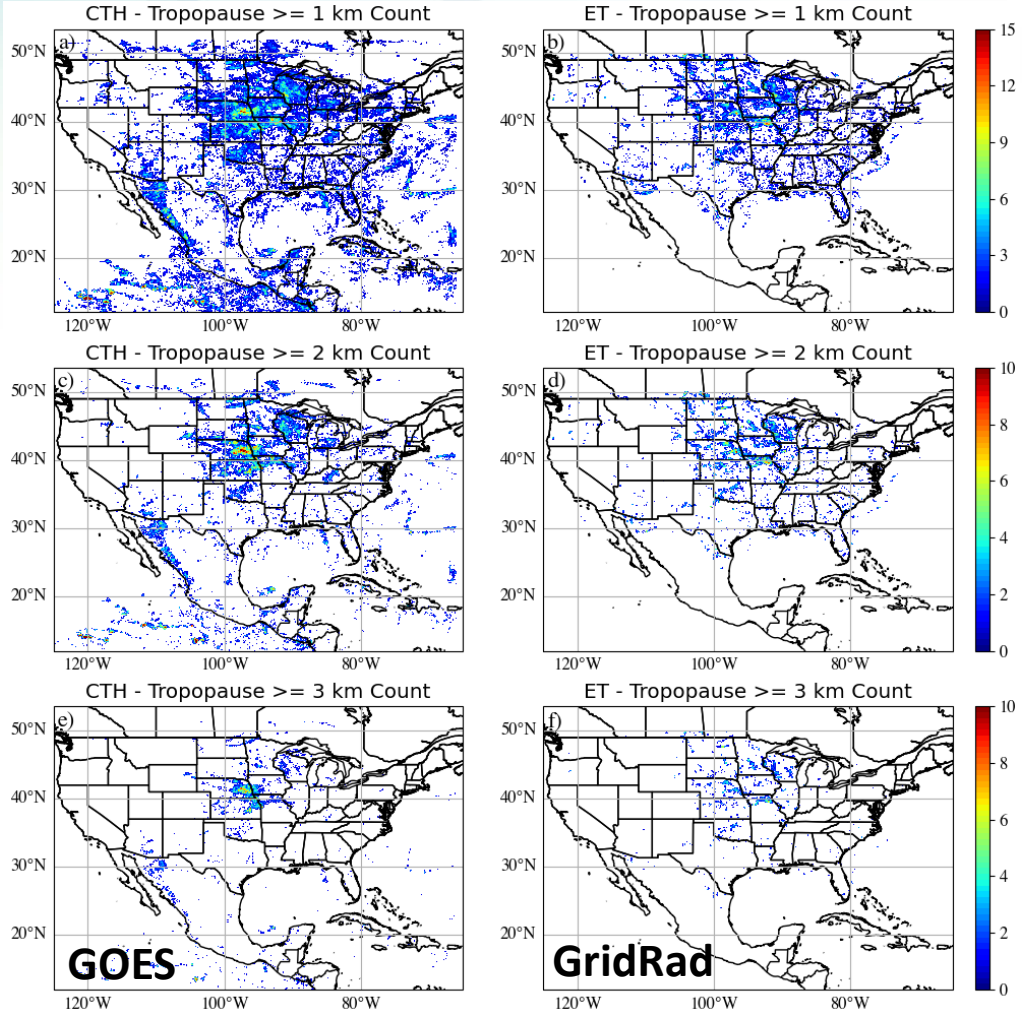
The object encompassed as much as 2316 km^2 in OT area from GridRad and 8392 km^2 from GOES-16

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

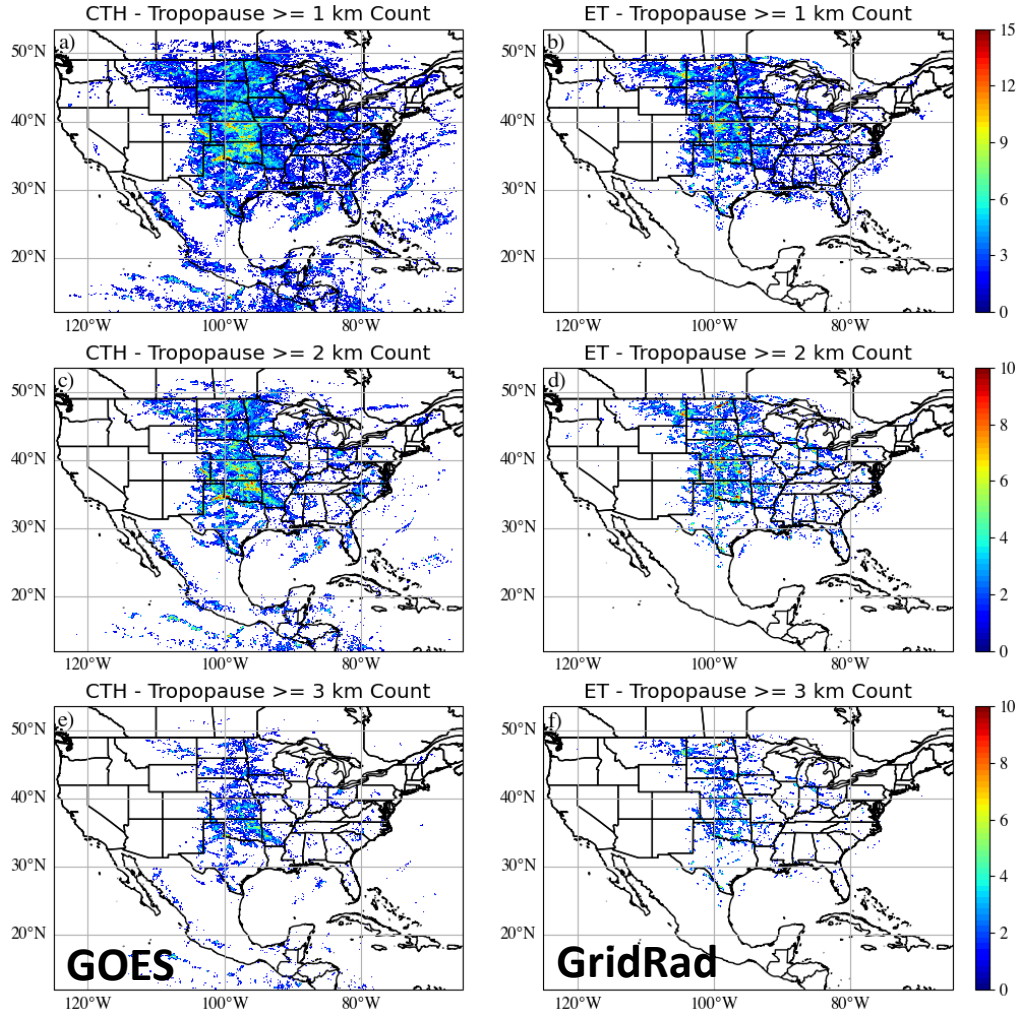
Spatial and Vertical Distribution of Overshooting During DCOTSS

- **Overshooting convection was more frequent in 2022 vs. 2021, due to a combination of seasonality and synoptic conditions**
- **GOES and GridRad agreed in terms of overshooting locations, but GOES depicted greater overshooting area, especially for shallow overshooting (< 1 km magnitude)**

DCOTSS 2021 (5 July – 22 August)



DCOTSS 2022 (12 May-13 July)



DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

DCOTSS Top 10 Object Lifetime Overshoot Volume Events

- **DCOTSS 2022 events, which were longer lived and more intense than 2021 on average, dominate the list**
- **Assuming IWC of 0.1 g/m^3, 1 km^3 of ice cloud weighs 1x10^5 kg. Based on this IWC assumption, these extreme events injected ~1.6-7.9 x 10^{10} kg (~16-79 Megatons) of ice cloud above the tropopause level based on the volume range depicted by GOES+GridRad**
  - Most studies have estimated convective hydration (in ppmv) via MLS, aircraft, sondes, and model simulations (e.g. Smith et al. JGR, 2017)
  - Liu et al. (ACP, 2010) estimated 2400-3300 tons/hour of total water injection from 2 African cases during SCOUT-AMMA using a model
  - The extreme DCOTSS events below produced 629,000-3,390,000 tons/hour
- **Significant uncertainty exists in terms of how much of the injected overshooting cloud material is detrained into the stratosphere outside of the overshooting core**

GOES

Start Date M/DD/YY HH:mm	Duration Hours	Volume km^3
6/9/22 19:10	30.5	790815.9
7/9/21 20:20	15.3	518582.9
8/7/21 21:40	25.8	484614.9
8/12/21 21:40	18.3	403559.7
5/17/22 22:30	19.7	391013.9
6/12/22 20:40	55.5	388219.4
5/31/22 21:30	17.7	385672.2
5/12/22 16:20	14.7	340844.9
5/24/22 18:00	32.5	337880.9
5/29/22 8:30	36.0	328517.6

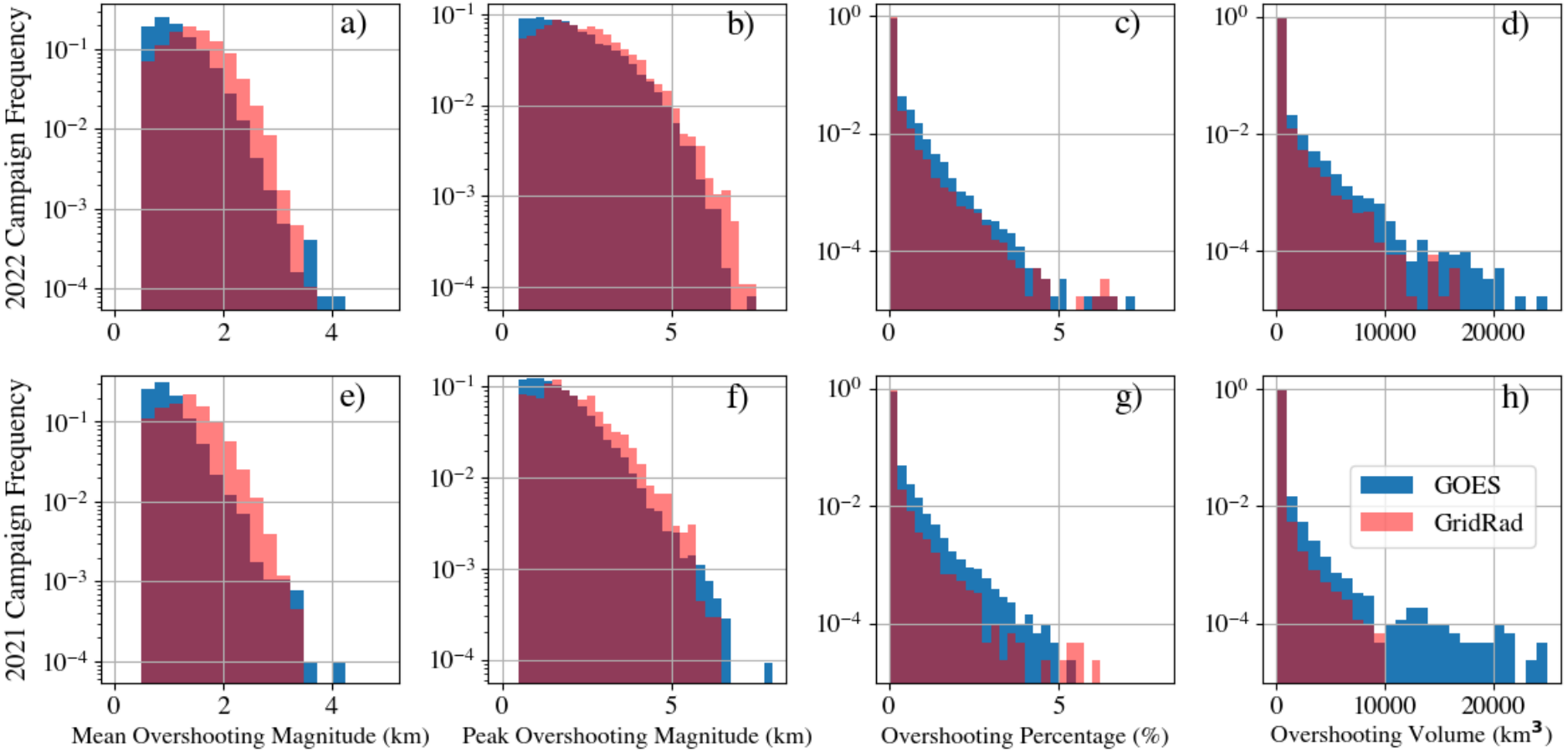
GridRad

Start Date M/DD/YY HH:mm	Duration Hours	Volume km^3
6/12/22 20:40	55.5	567615.4
7/9/22 21:30	28.3	301453.7
5/12/22 16:20	14.7	210804.2
5/29/22 8:30	36.0	199440.2
6/24/22 19:20	16.5	189800.6
6/11/22 21:30	11.3	186221.2
7/28/21 22:20	13.0	184524.5
7/8/22 21:40	21.8	169081.1
5/31/22 21:30	17.7	168213.9
5/15/22 7:50	26.5	166747.5

Red: Events Common To Both GOES and GridRad

DCOTSS 2021 and 2022 Overshooting Metrics *(10-min Timesteps Over CONUS)*

- **As shown in previous case studies, GridRad detects greater overshoot magnitude but GOES detects greater overshoot area (i.e. percentage of anvil area)**
- **Overshooting seldomly exceeds 5% of the anvil area, and is most commonly 0-2%**
- **Overshoot area differences are the primary driver of differences in overshoot volume**

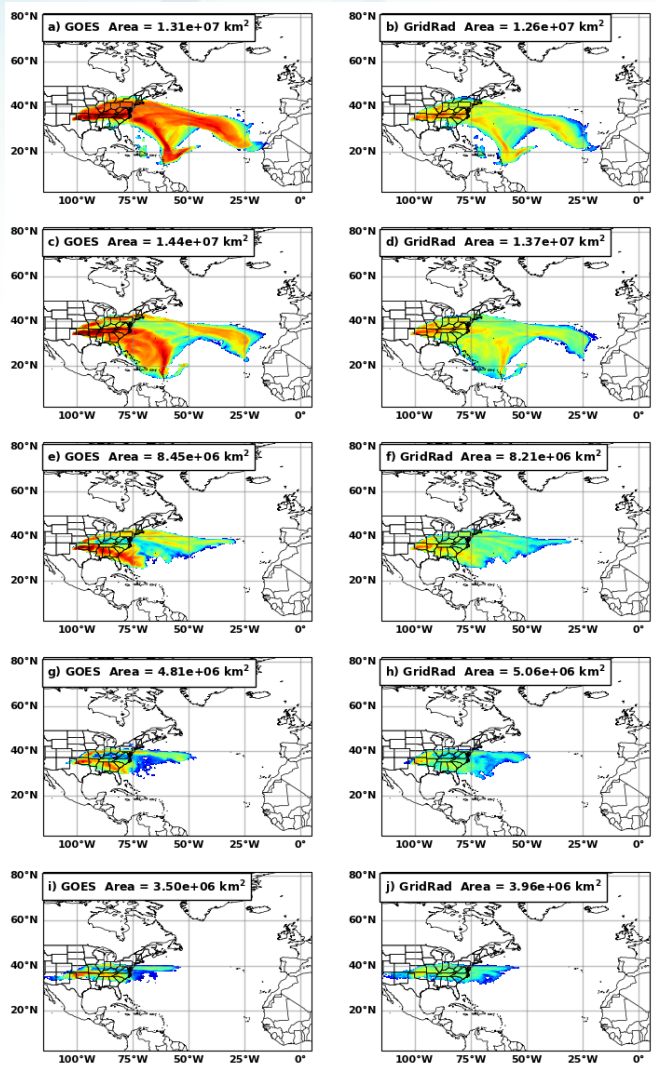


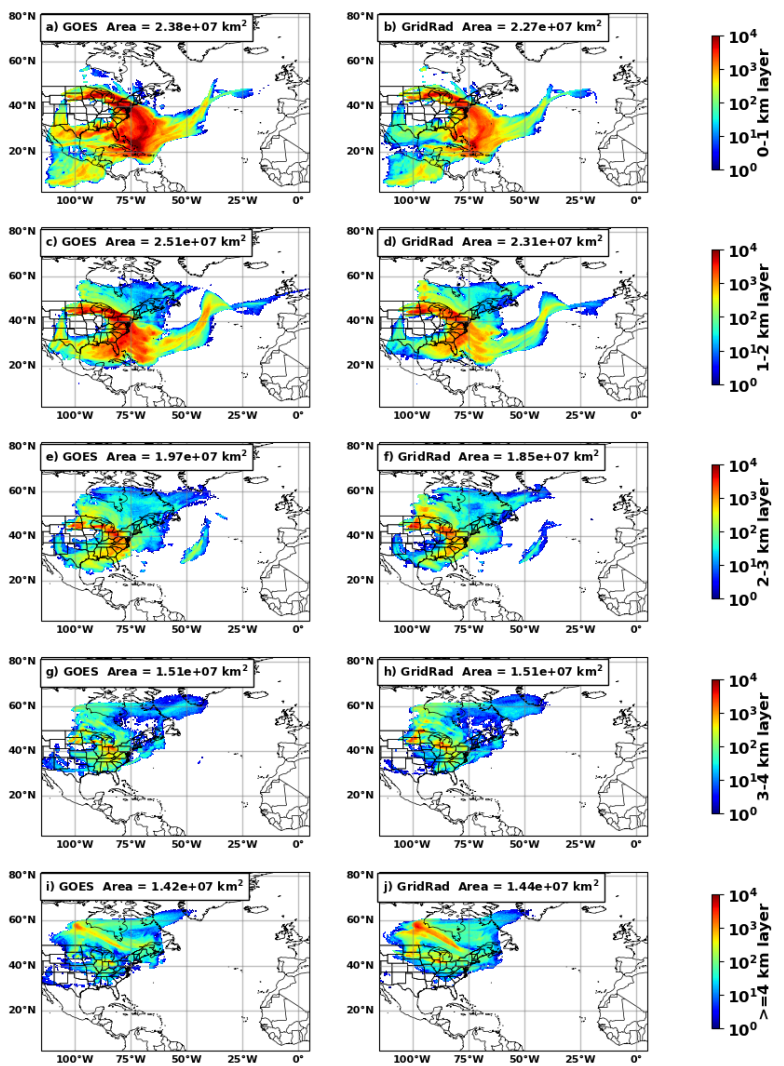
DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

How Broadly Can A Convective Storm Outbreak Impact The Stratosphere?

- Air parcel trajectories initialized at overshooting locations and advected forward 5 days using ERA-5 dynamics showed extremely good agreement in terms of parcel location, but some differences in density
- Extreme outbreaks like these can influence broad regions deep into the stratosphere in the days following the event

31 May – 1 June 2022 Event





12-15 June 2022 Event

DCOTSS
NASA Earth Venture Suborbital 3
Dynamics and Chemistry of the Summer Stratosphere

Summary and Uncertainties

- **Though there are differences between GOES and NEXRAD depictions of overshooting volume, they are on same order of magnitude when aggregated at the storm lifetime scale using a novel object tracking framework, revealing that convection injects a significant amount of ice above the tropopause level**
- **The air volume injected into the stratosphere over the CONUS ranged from 2,178,154 - 5,360,162 km^3 in 2021 and 6,017,486 – 10,642,008 km^3 in 2022, with GOES being higher than GridRad during both years**
- **Assuming an IWC of 0.1 g/m^3, storms during DCOTSS injected ~218-536 MT of ice in 2021 and ~602-1064 MT in 2022**

Key Uncertainties

- **What fraction of injected cloud material is detrained into the stratosphere and how does it sublimate into water vapor?**
- **Assumed relationship between IR temperature and cloud top height (3.25 K/km cooling rate) within OTs**
- **Tropopause height uncertainty between models (i.e. MERRA-2 vs ERA-5)**
- **How much does injected volume vary between the 10-min GOES+GridRad sampling intervals?**

Read More About This Study:

Itterly, K. F, K. M. Bedka, C. R. Homeyer, and K. Khlopenkov, 2024: Quantifying Tropopause-Overshooting Volume from Satellite and Radar Observations during DCOTSS 2021 and 2022 Campaigns. ESS Open Archive. *In Review for the Journal of Geophysical Research-Atmospheres*