Use Of GOES Super Rapid Scan Imagery For Analysis and Automated Detection of Ice Crystal Icing and Severe Weather Hazards

Kristopher Bedka[1], Konstantin Khlopenkov[2], Christopher Yost[2], Benjamin Scarino[2], Cameron Homeyer[3], Thea Sandmael[3], Elisa Murillo[3], Walter Strapp[4], John Mecikalski[5], Jason Apke[6], and John Cooney[7]

[1] NASA Langley Research Center, [2] Science Systems and Applications, Inc., [3] University of Oklahoma, [4] Met Analytics, Inc, [5] University of Alabama in Huntsville, [6] CIRA / Colorado State University, [7] Texas A&M University

Email Contact: kristopher.m.bedka@nasa.gov

Severe Thunderstorm Research

Introduction

The GOES-R series satellites are collecting observations of severe storms at unprecedented detail. Nearly every day, GOES-16/17 collects ABI visible and infrared (IR) imagery of storms at 1-minute or better resolution. When paired with GLM data, these ABI "Mesoscale Domain Sector" (MDS) observations allow us to infer processes that are occurring within storm updrafts and cloud tops via wind flows, temperature, visible texture, and lightning-generated radiances that can be detected using automated algorithms. Prior to the GOES-R series, GOES-8 to -15 observations were relatively coarse which limited their utility in severe storm forecasting after a storm became mature. GOES-R MDS data provides a new opportunity to determine how satellite-derived products could contribute to our understanding and detection of severe storms. This poster highlights recent research on severe storms supported by the NASA Weather and Atmospheric Dynamics Focus Area.

Goals

Use automated tracking and fusion of GOES, NEXRAD GridRad, and ENTLN lightning flash rate at 1-minute intervals at the individual storm cell scale to:

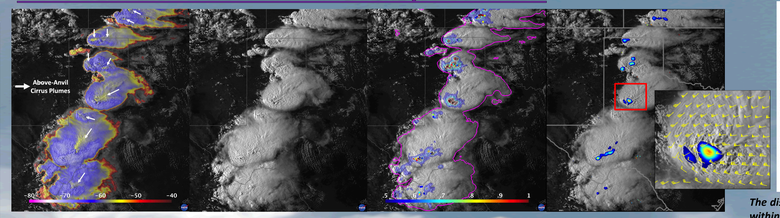
1) Detect known satellite-observed signatures indicative of convection and severe weather such as anvil clouds, overshooting tops, and gravity waves. Characterize storm intensity via storm updraft penetration above the surrounding anvil and tropopause, visible texture magnitude, cloud top height, divergence and vorticity within cloud tops, and optical thickness

2) Quantify relationships and time evolution of GOES, radar, lightning, NWP, and severe storm metrics (e.g. NWS warnings, spotter reports, radar MESH)

3) Better understand what is happening within storms when signatures such as the enhanced-V and above-anvil cirrus plume (AACP) appear, and how can recognition of these signatures aid severe storm warning

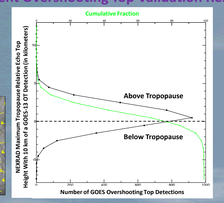
4) Better understand how ABI, GLM, and radar observations can be combined in a statistical sense to improve severe storm detection (Mecikalski talk, Wednesday at 2 PM)

GOES Convection Detection and Analysis Products



(A) GOES-16 Infrared With Above Anvil Cirrus Plume Locations Identified, 5 May 2019 at 2330 UTC, (B) GOES-16 Visible (C) Visible Texture Magnitude (Color Shading), IR Overshooting Top Detection (Colored Dots, see color table), and Anvil Detections (Magenta Contour), (D) GOES Cloud Top Divergence derived from visible AMVs using optical flow (color shaded) with a zoomed inset of a supercell in the center of the domain.

Recent Overshooting Top Validation Results

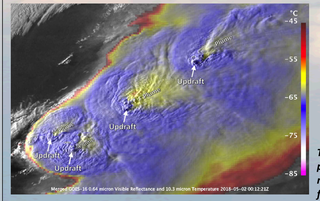


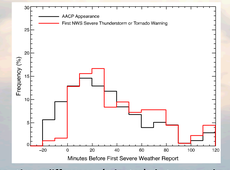
The distribution NEXRAD maximum echo top heights within 10 km of GOES-13 IR overshooting top detections. Echo top height was shown to increase in conjunction with the magnitude of visible texture. NEXRAD overshoots were within 10 km of a GOES overshoot 63% of the time. 55% of all NEXRAD overshoots were detected.
From John Cooney (PhD Dissertation, Texas A&M)

Above Anvil Cirrus Plume Research

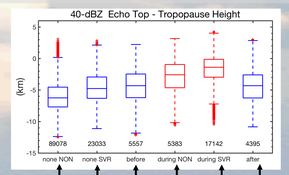
Background Information (From Bedka et al. 2018)

13 severe weather outbreaks were studied using GOES-14 and -16, 30-sec to 1-min imagery. 8000+ GOES images were manually analyzed to identify plumes. 405 plume producing storm cells were identified by a team of human experts. 4178 other non-plume producing storms were also analyzed. The starting and ending time of plume production was recorded. Radar-detected cells must persist for 10+ mins to be included in the analysis. 4503 hail, wind, and tornado reports were generated by 700 severe storm cells. 807 significant severe reports, 2+ inch hail, 65+ kt wind, EF-2+ tornado, occurred. NOAA NCEI Storm Events Database was used to define severe weather. Severe thunderstorm and tornado warnings were acquired from the Iowa Environmental Mesonet website.

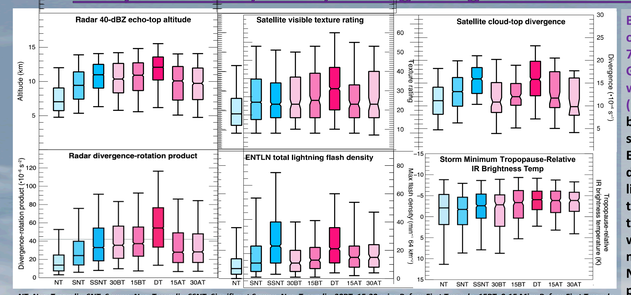




The time difference (minutes) between when a plume first appeared and the first severe weather report (black), and the time difference between the first NWS severe thunderstorm or tornado warning and first severe weather report (red).



Analysis of GOES, Radar, and Lightning Data Prior To and During Severe Weather



NT: Non-Tornadic, SNT: Severe, Non-Tornadic, SSNT: Significant Severe, Non-Tornadic, 30BT: 15-30 mins Before First Tornado, 15BT: 0-15 Mins Before First Tornado, DT: During Tornado, 15AT: 0-15 Mins After The Last Tornado, 30AT: 15-30 mins After The Last Tornado

Based on analyses of 7280 storm cells (~150,000 minutes of storm lifetime), 978 of which were severe and produced 777 tornadoes, nearly all measures of storm intensity from GOES-13/14, radar, and lightning data show that updrafts were most intense when tornadoes were on the ground (DT, left panels). There is significant overlap in parameters between tornadic storms and storms that produce significant severe weather (SSNT, 5+ cm hail, 65+kt wind, EF-2+ tornadoes), so one cannot use a single threshold to discriminate a tornadic storm especially in the case of lightning flash density. The storm minimum IR brightness temperature is comparably cold for all storm types, but tornadoes seldom occurred when temperatures were warmer than the tropopause. Visible texture is a better metric of updraft intensity than IR temp. The product of NEXRAD upper-level (8+ km) divergence and rotation provided the largest separation between tornadic and non-tornadic storms. An objective threshold method based on this product provides early indication of potentially tornadic storms with comparable performance to NWS tornado warnings. From Sandmael et al. (2019), radar data processed within GridRad (www.gridrad.org)

Above Anvil Cirrus Plume Research: Key Findings

The results of this study demonstrate that, on average, storms that produce above anvil plumes are an especially intense subset of deep convection, featuring the highest cloud tops, strongest updrafts, most lightning, and a high frequency of severe weather

Plume-producing storms generated 14 times more severe weather reports per storm than storms without plumes

59% of plume storms were severe, and plume storms generated the majority (57%) of all severe reports across the 13 outbreaks. 73% of the 5+ cm hail, 65+ kt wind, and EF-2+ tornadoes generated by plume storms

48% of plume storms were supercells defined using a combination of quantitative and qualitative analyses. 75% of supercells produced plumes

Mean duration of plume production was ~50 mins. Some storms produced plumes almost continuously for over 4 hours

Though storms without plumes often generate severe weather, a plume is better correlated with severe weather than any other known GOES cloud-top signature

In areas with poor or non-existent radar coverage, a plume can be used to quickly recognize significant severe storms using satellite imagery alone

GOES 1-minute imagery is extremely valuable for plume identification and for defining quantitative relationships with radar and lightning datasets, and severe weather reports/warnings

References

Apke, J.M., J.R. Mecikalski, K. Bedka, E.W. McCaul, C.R. Homeyer, and C.P. Jewett, 2018: Relationships between Deep Convection Updraft Characteristics and Satellite-Based Super Rapid Scan Mesoscale Atmospheric Motion Vector–Derived Flow. Mon. Wea. Rev., 146, 3461–3480, https://doi.org/10.1175/MWR-D-18-0119.1

Bedka, K. M., C. Wang, R. Rogers, L. Carey, W. Feltz, and J. Kanak, 2015: Examining deep convective cloud evolution using total lightning, WSR-88D, and GOES-14 super rapid scan datasets. Wea. Forecasting, 30, 571-590.

Bedka, K. M., and K. Khlopenkov, 2016: A probabilistic pattern recognition method for detection of overshooting cloud tops using satellite imager data. J. Appl. Meteor. Climatol. 55, 1983–2005, https://doi: 10.1175/JAMC-D-15-0249.

Bedka, K., E.M. Murillo, C.R. Homeyer, B. Scarino, and H. Mersiovsky, 2018: The Above-Anvil Cirrus Plume: An Important Severe Weather Indicator in Visible and Infrared Satellite Imagery. Wea. Forecasting, 33, 1159–1181, https://doi.org/10.1175/WAF-D-18-0040.1

Homeyer, C.R., J.D. McAuliffe, and K. M. Bedka, 2017: On the Development of Above-Anvil Cirrus Plumes in Extratropical Convection. J. Atmos. Sci., doi: 10.1175/JAS-D-16-0269.1.

Mecikalski, J. R. T. N. Sandmael, E. M. Murillo, C. R. Homeyer, K. M. Bedka, J. M. Apke, C. P. Jewett, 2019: A Statistical Model to Nowcast Severe Storms using High-Resolution Radar, GOES Satellite, and Lightning Observations. Submitted to Monthly Weather Review

Murillo, E.M. and C.R. Homeyer, 2019: Severe Hail Fall and Hailstorm Detection Using Remote Sensing Observations. J. Appl. Meteor. Climatol., 58, 947–970, https://doi.org/10.1175/JAMC-D-18-0247.1

Sandmael, T., C. R. Homeyer, K. M. Bedka, J. M. Apke, J. R. Mecikalski, and K. Khlopenkov, 2019: Evaluating the ability of remote sensing observations to identify significantly severe and potentially tornadic storms. Accepted to J. Appl. Meteor. and Climatol.

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Analysis and Detection Of Convectively-Induced Icing Conditions From High Ice Water Content (HIWC)

Introduction

Recent studies have found that high mass concentrations of ice particles within deep convective storm anvils can adversely impact aircraft engine and air probe (e.g. pitot tube and air temperature) performance. Radar reflectivity in these regions suggests that they are safe for aircraft penetration, yet high ice water content (HIWC) is still encountered. The aviation weather community seeks additional remote sensing methods for delineating where icing conditions are likely, including products derived from geostationary (GEO) satellite imagery that is now available in near-real time at increasingly high spatio-temporal detail. Previous analyses of GEO imagery of in-service aircraft engine icing events (Bravin et al. 2019; Strapp et al. 2019) indicate that aircraft flew for long duration in close proximity to cloud tops above the equilibrium level. These strong updrafts likely generated and transported HIWC to the anvil.

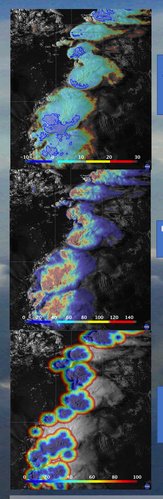
Seven NASA DC-8 aircraft flights were conducted in August 2018 over the Gulf of Mexico and the tropical Pacific Ocean during the HIWC Radar II field campaign. The DC-8 was equipped with an in-situ isokinetic evaporator probe (IKP-2) that measures total water content (TWC) at 1-second intervals. The convection sampled during four flights was observed by GOES-16 at 1- or 5-minute intervals, which provided some of the best-ever time synchronization with IKP-2 data. These data, in addition to that from 50 previous flights with the NASA DC-8 during 2015 HIWC Radar I and the 2014 and 2015 international HAIC/HIWC campaigns, enable us to understand the characteristics of convection when HIWC is measured and to develop new automated detection products to delineate where HIWC is likely. This presentation highlight analyses from these recent airborne campaigns, focusing on flights monitored with 1-minute GOES-14 and -16 imagery.

Goals

Understand the temporal evolution, and spatial and multispectral characteristics of clouds when HIWC (IKP-2 TWC > 1.0 g m^{-3}) is encountered

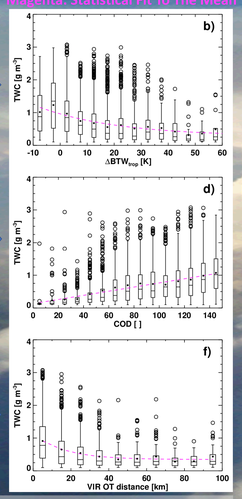
Determine how well we can discriminate HIWC from clouds with low to moderate TWC

Develop a new HIWC likelihood product using imagery and products that can be produced anywhere across the world in near real-time



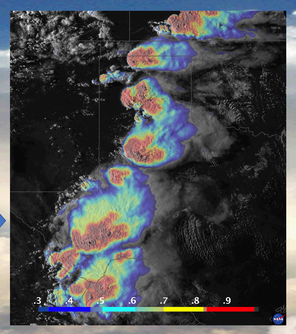
MTSAT-1R and GOES-13/14 Relationships With In-Situ Ice Water Content

Magenta: Statistical Fit To The Mean

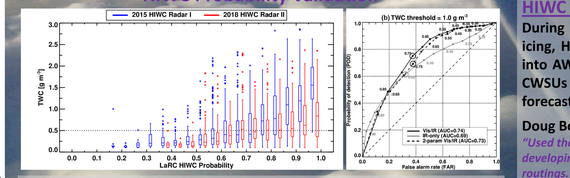


A large sample of co-located GEO satellite and in-situ IKP-2 TWC datasets across 50 research aircraft flights found that optically thick clouds with tops near to or above the tropopause in close proximity (≤ 40 km) to convective updrafts were most likely to contain TWC ≥ 1 g m^{-3}, a threshold considered hazardous for aircraft (Yost el al. (AMT, 2018)). These parameters are detected using automated algorithms and combined to generate a HIWC probability product at the NASA LaRC.

NASA LaRC HIWC Probability Product

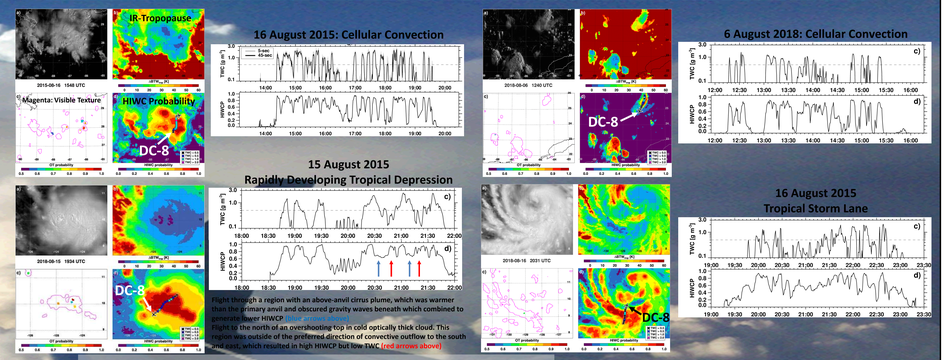


HIWC Probability Validation



(Left) The distribution of TWC as a function of HIWC Probability (PHIWC), binned at 0.05 intervals during NASA DC-8 HIWC Radar I (blue) and HIWC Radar II (red). It is was found that, given a similar set of cloud characteristics that produce the same PHIWC, the TWC was lower on average in the 2018 campaign. This is thought to be related to the fact that sampled storms were more vigorous with greater ice content in 2015. (Right) A ROC curve showing the relationship between POD and FAR for PHIWC thresholds ranging from 0.0 to 1.0 (labeled at 0.1 increments) based on HIWC defined by TWC > 1.0 g m^{-3}. The solid black curve represents the three-parameter $PHIWC_{day}$ and the solid grey curve represents the two-parameter $PHIWC_{night}$. The dashed black curve represents an algorithm formulation using IR-tropopause and distance to OT (dOT) analogous to $PHIWC_{night}$ but VIS texture detections in addition to IR OT detections are used to derive dOT. These results were based on data from the 2014 and 2015 HAIC/HIWC campaigns and HIWC Radar I.

GOES-14 and GOES-16 1-Minute HIWC Probability Vs Cloud Ice Water Content



HIWC Product Evaluation By Weather Service Forecasters

During Spring 2019, NASA LaRC GOES-16 supercooled water airframe icing, HIWC, and overshooting top detection products were integrated into AWIPS-II and provided to the Fort Worth, Houston, and Memphis CWSUs at 5-minute intervals for evaluation by NOAA aviation weather forecasters, in collaboration with NASA MSFC SPoRT

Doug Boyette, Meteorologist in Charge, Memphis CWSU

"Used the convective products to get an idea of areas of weakness/holes were developing in several linear convective features affecting large scale air traffic routings. HIWC and visible texture were particularly helpful, and IR overshooting tops gave me a quick idea of the best updrafts." (4/7/2019)

Roland Nunez, Meteorologist in Charge, Houston CWSU

"The HIWC and Visible Texture Rating (VTR) products were exceptional in showing the likely hazards due to icing and turbulence…. Though SPC mesoanalysis and HREF ensembles provides confidence on the long term storm development with our airspace, HIWC and VTR showed the enormity of the hazards at onset and throughout this event. …HIWC and VTR provide hazard information in near-real time at a spatial and temporal resolution that is not replicated in any other available product." (5/14/2019)

"Over the oceanic airspace, where no AIRMETs were available, these convective products are a huge asset. Some ocean routes ended up being closed and these products substantiated the need for closures." (5/8/2019)

References

Bedka, K. M., C. Yost, L. Nguyen, W. Strapp, T. Ratvasky, K. Khlopenkov, B. Scarino, R. Bhatt, D. Spangenberg, R. Palikonda, 2019: Analysis and Automated Detection of Ice Crystal Icing Conditions Using Geostationary Satellite Datasets and In Situ Ice Water Content Measurements. *Proceedings of the 2019 SAE International Conference on Icing of Aircraft, Engines, and Structures.*

Bravin, M., J.W. Strapp, M. Grzych, and M. Clarkson, 2019: A Continuing Investigation of Diurnal and Location Trends in an Ice Crystal Icing Engine Event Data Base", Proceedings of the 2019 SAE International Conference on Icing of Aircraft, Engines, and Structures.

Haggerty, J., E. Defer, A. De Laat, K. Bedka, J. Moisselin, R. Potts, J. Delanoë, F. Parol, A. Grandin, and S. Divito, 2019: Detecting Clouds Associated with Jet Engine Ice Crystal Icing. Bull. Amer. Meteor. Soc., 100, 31–40, https://doi.org/10.1175/BAMS-D-17-0252.1

Ratvasky, T., W. Strapp, L. Lillie, F. Proctor, J. Strickland, P. Hunt, K. Bedka, G. Diskin, J. Nowak, T. P. Bui, A. Bansemer, C. Dumont, 2019: Summary of the High Ice Water Content (HIWC) RADAR Flight Campaigns. Proceedings of the 2019 SAE International Conference on Icing of Aircraft, Engines, and Structures.

Strapp, J.W., Schwarzenboeck, A., Bedka, K., Bond, T., et al., 2019: An Assessment of Cloud Total Water Content and Particle Size from Flight Test Campaign Measurements in High Ice Water Content, Mixed Phase/Ice Crystal Icing Conditions: Primary In-Situ Measurements, DOT/FAA/TC-18/1, Under FAA Review.

Yost, C. R., Bedka, K. M., Minnis, P., Nguyen, L., Strapp, J. W., Palikonda, R., Khlopenkov, K., Spangenberg, D., Smith Jr., W. L., Protat, A., and Delanoe, J., 2018: A prototype method for diagnosing high ice water content probability using satellite imager data, Atmos. Meas. Tech., 11, 1615-1637, https://doi.org/10.5194/amt-11-1615-2018

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