OBJECTIVE SATELLITE-BASED OVERSHOOTING TOP AND ENHANCED-V/COLD RING DETECTION: VALIDATION AND RELATIONSHIPS WITH SEVERE WEATHER

Kristopher Bedka[1], Jason Brunner[2], Richard Dworak[2], and Wayne Feltz[2]
[1]*SSAI @ NASA Langley, 1 Enterprise Pkwy., Suite 200, Hampton, VA USA, email: kristopher.m.bedka@nasa.gov*
[2] *University of Wisconsin-Madison SSEC/CIMSS, 1225 W. Dayton St., Madison, WI USA*

I. INTRODUCTION

Overshooting tops (OTs) are the product of deep convective storm updrafts of sufficient strength to rise above the storms' general equilibrium level near the tropopause region and penetrate into the lower stratosphere. OTs appear in ~11 µm longwave IR window (IRW) imagery as a small cluster (< 15 km diameter) of very cold pixels relative to the surrounding cirrus anvil cloud. An OT with a significant vertical protrusion above the anvil cloud can act as an obstruction to the jet stream wind flow. This contributes to producing the enhanced-V signature in IR satellite imagery. The cold-ring signature is related to the enhanced-V but has been shown to form in environments with weaker jet stream wind flow than enhanced-V cases. A region of anomalously warm IRW brightness temperatures (BTs) is often found downstream of the OT region. The combination of the cold OT signature and downstream warm region within the enhanced-V is referred to here as an anvil thermal couplet (ATC, see Fig. 1).

Thunderstorms with OTs frequently produce hazardous weather at the Earth's surface such as heavy rainfall, damaging winds, large hail, and tornadoes. Maximum radar reflectivity and precipitation echo top height is found at or near the time of OT detections (Dworak et al. 2011). Thunderstorms with a strong ATC signature (i.e. OT minus warm region BT diff > 10 K) have been shown to be especially severe (Brunner et al. 2007).

Due to the hazardous nature of storms with OTs, objective OT and enhanced-V signature detection is a product requirement for the GOES-R Advanced Baseline Imager (ABI) program (http://www.goes-r.gov/products/opt2-enhanced-V.html). An objective OT detection product has been developed in support of the ABI program that focuses on the attributes of OTs as depicted in IRW imagery (Bedka et al. 2010). This product uses a combination of: 1) tropopause temperature from an NWP model and 2) IRW BT and spatial BT gradient criteria defined through detailed analysis of a database of OT-producing thunderstorm events observed by MODIS, AVHRR, GOES, and SEVIRI. Clusters of pixels significantly colder than the surrounding anvil cloud with a diameter consistent with commonly observed OTs are identified with this approach. This method is referred to here as "IRW-texture" since it takes into account spatial IRW BT gradients (i.e. texture). Once OTs are detected, pixels within 35 km of the OT and +/- 45° of the jet stream wind vector are examined to determine the presence of a downstream warm region typically found within the enhanced-V or cold-ring signature. This algorithm is highly efficient in that it can process over the entirety of Europe or the US in under 30 seconds, allowing for processing real-time rapid scan imagery or with large volumes of archived global GEO and polar-orbiting satellite data.

It is important to assess the accuracy of these satellite-based detection algorithms so forecasters can develop confidence in product output. While OTs and enhanced-V signatures have been shown to be well correlated with severe weather in limited case study-based comparisons (see Fig. 2), it is important to demonstrate robust statistical relationships between satellite-observed signatures and severe weather reports so forecasters can understand how observations of these signatures and their objective detection can be used to diagnose and warn for severe weather. This paper briefly summarizes recent product validation studies and comparisons with observed severe weather defined by damaging wind (> 50 kt), hail (> 2.5 cm), and tornadoes over the U.S. and Europe.

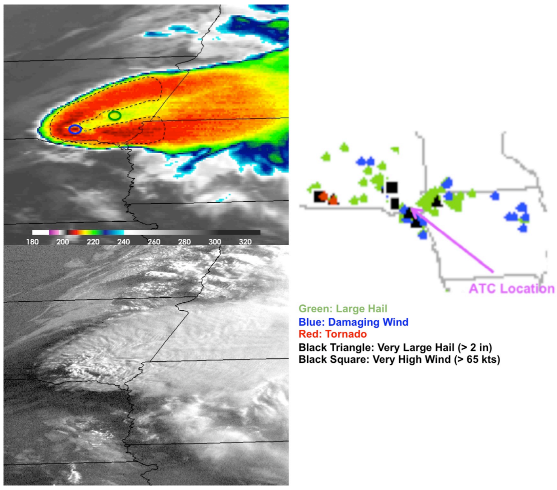

FIG. 1: (Left) GOES-12 10.7 µm IRW (top) and visible (bottom) channel imagery of a enhanced-V producing storm over the U.S. Northern Plains on 9 July 2009. The locations of OT (blue circle) and downstream warm region (green circle) detections are shown atop the IRW image (Right) A map of severe weather reports from 9 July showing that this storm was producing large hail and damaging winds at the time of the image.

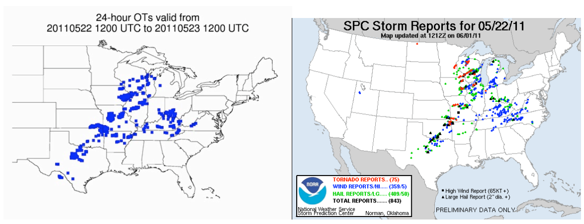

FIG 2: (left) A 24-hour accumulation of OT detection output between 1200 UTC on 22 May 2011 and 1145 UTC on 23 May 2011. (right) An accumulation of damaging wind, large hail, and tornado reports during the same time period.

II. DATASETS AND METHODOLOGY

It is a challenge to validate objective OT and enhanced-V/cold-ring signature detections because little to no "truth" datasets exist. Nevertheless, techniques must be developed to demonstrate that these algorithms exceed the 75% detection accuracy (defined by 1 minus the False Alarm Rate (FAR)) mandated by the GOES-R program.

Observations of OTs from the NASA CloudSat instrument and the U.S. National Weather Service

NEXRAD ground-based radar network have been used to validate OT detections. CloudSat data were manually investigated over a 1.5 year period to find deep convective cloud tops at or near the tropopause with a height at least 0.5 km above the surrounding anvil cloud. The number of OTs observed by CloudSat is significantly limited by CloudSat ~1.5 km field of view and the fact that it passes over the equator at 1:30 AM/PM local time which misses the time of peak convective storm frequency and intensity. 111 total OTs were found within ~3000 CloudSat orbits over the 1.5 year study period. Imagery from MODIS and the current constellation of GEO instruments including GOES-12 and MSG SEVIRI have been processed within the OT detection algorithm and compared with the CloudSat OT database to determine product FAR and probability of detection (POD). MODIS data is degraded to the 2 km GOES-R ABI spatial resolution to estimate future algorithm performance. See Bedka et al. (2011) for detailed validation methodology.

The peak height of the 18 dBZ echo within a vertical column of data observed by the U.S. NEXRAD radar network is compared with NWP tropopause data to infer OT locations. This 5-minute and 1 km resolution "echo top" product has been provided by the NOAA National Severe Storms Laboratory for the 2009-2010. Echo tops must be above the tropopause minus 0.5 km to be considered OTs since the precipitation echoes will be found a significant distance below the physical cloud top that is overshooting the tropopuase. OT detections from GOES-13 are compared with NEXRAD OT to determine product FAR.

628 enhanced-V and cold-ring events distributed across 196 scenes over the U.S were manually identified in MODIS and AVHRR imagery. Synthetic MODIS- and AVHRR-based 2 km ABI imagery were processed within the enhanced-V/cold-ring detection algorithm over large geographic regions including the enhanced-V producing storm. It is estimated that 5000+ individual deep convective clouds were found within the 196 scenes, providing ample opportunity for algorithm false alarm. Severe storm reports near the time of these scenes are also be analyzed.

Reports of damaging wind, large hail, and tornadoes collected by the NOAA Storm Prediction Center were compared with GOES-12 OT detections from 2004-2009. An OT detection is considered to be associated with a severe storm if it is within 30 min and 30 km of the reported severe weather location. Similar studies have been performed during the 2004-2009 time period using MSG SEVIRI imagery in conjunction with the European Severe Weather Database (Bedka 2011). It is important to remember that OTs may not occur or be present in satellite imagery in marginal thermodynamic or very dynamic wind shear environments, so a "missed detection" should not imply an inadequacy of the objective satellite product.

III. DETECTION VALIDATION AND RELATIONSHIPS WITH SEVERE WEATHER

a. OT Detection Validation

Fig. 3 provides an example of a CloudSat observed OT, time-matched MODIS imagery, and OT detections using the Bedka et al. IRW-texture method and WV-IRW BT difference (BTD) methods (Setvak et al. 2007 and references therein) for an event over the South Pacific. The CloudSat Cloud Profiling Radar profile shows that this OT was 1.5 km above the surrounding anvil with a diameter of ~15 km. The OT is correlated with a small region of cold (205 K) IRW BTs. The IRW-texture method detected this OT and numerous other regions associated with the characteristic "lumpy" texture of OTs in visible imagery. The WV-IRW BTD method also detected this OT in addition to much of the deep convective anvil cloud, which would suggest that this technique produces a significant false detection.

Objective validation of the IRW-texture method using synthetic ABI imagery for the 111 CloudSat events indicates an OT POD of 76% and a FAR of 17%. When current GEO data is used as input, the POD drops to 55% but the FAR remains the same. Current GEO imager spatial resolution ranges from 3 km (MSG SEVIRI) to 5 km (MTSAT). Comparison of IRW BTs between MODIS and 4 km GOES for 125 random OT events indicated that MODIS was 12 K colder than GOES on average while the surrounding anvil BT remained nearly the same (not shown). Thus, an OT signature would appear more prominently in higher spatial resolution imagery and would be readily detected by the IRW-texture method. Validation of the WV-IRW BTD method indicates an OT POD of 96% and a FAR of 81%. These statistics coupled with the results from Fig. 3 suggest that the WV-IRW BTD may better serve as a deep convective cloud mask than an OT detection product.

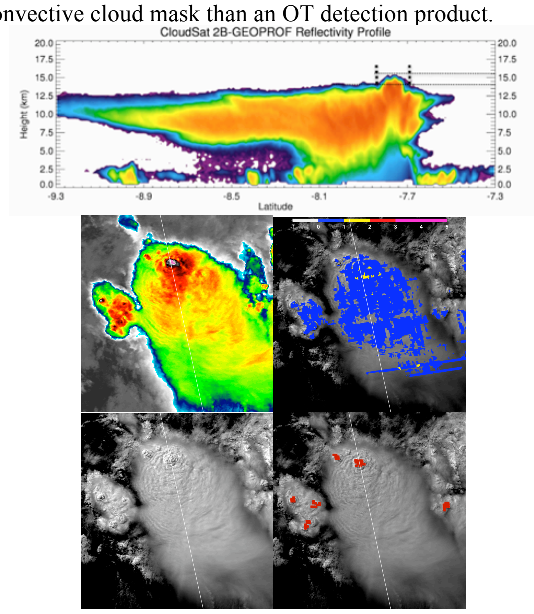

FIG. 3: (top) CloudSat Cloud Profiling Radar data for an OT-producing storm over the South Pacific on 9 May 2008 at 2317 UTC. (bottom, upper-left) MODIS 1 km IRW imagery. The white line shows the location of the CloudSat overpass (upper-right) WV-IRW BTD > 0 K, (lower-left) MODIS 0.25 km visible imagery. (lower-right) OT detections overlaid upon visible imagery

GOES-13 satellite imagery, IRW-texture OT detection output, NEXRAD composite radar reflectivity and echo top data shown in Fig. 4 at a time just prior to the Parkersburg, IA F5 tornado. The OT region corresponds with the coldest IRW BTs, heaviest precipitation, and echo tops above 60 kft. OT detections were subsequently found in GOES rapid-scan imagery while the tornado was on the ground. Observations of OT signatures in conjunction with vertical profiles of radar reflectivity indicate that the timing of satellite OT signatures is well correlated with maxima in radar reflectivity aloft. (Dworak et al. 2011, not shown here). These precipitation maxima descend to the lowest elevation scan 5-10 mins after the OT observation as the storm updraft weakens or pulses in intensity. Comparisons of GOES-13 OT detection output with NEXRAD echo top OT inferences indicate an FAR of 5.9% during Spring 2009 and 3.4% during Spring 2010.

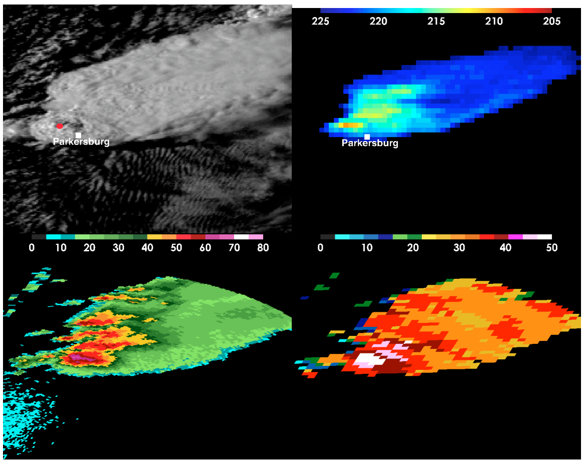

FIG 4: (upper-left) GOES-12 visible imagery with an OT detection (red dot) on 25 May 2008 at 2145 UTC. (upper-right) GOES-12 4 km IRW imagery. Only IRW BT < 225 K is shown. (lower-left) Des Moines, IA NEXRAD composite reflectivity. (lower-right) NEXRAD echo top (in kft).

b. OT Relationships With Severe Weather

A comparison of OT detection output with severe weather reports for the 22-23 May 2011 severe weather outbreak (including the Joplin, Missouri F5 tornado event) shows a strong correlation between the two fields (Fig. 2), but it is clear that not every detection was near a severe storm and some severe storms were undetected. A comparison between OT detections and U.S. severe weather from 2004-2009 indicate that OTs were detected near 50% of severe storms and 25% of all OTs were associated with a severe storm report (Dworak et al. 2011). For comparison, OTs were found near 44% of European severe weather (Bedka 2011, small sample size precluded the inverse OT-to-severe weather comparison). Statistics for U.S. and Europe were comparable for large hail and damaging winds (> 50%), but significantly different for tornadic storms (14% Europe vs. 56% U.S.). The reasons for these differences are not yet understood. Fig. 5 shows that the OT detection-severe weather relationship increases with decreasing IRW BT. If any combination of severe weather is considered, 49% of OTs with an IRW BT < 196 K are associated with severe weather. For this same temperature, a storm will produce only hail for 22% of OT detections. It is also clear that an OT pixel with an IRW BT < 210 K is more often severe than a pixel with the same IRW BT that does not meet the OT detection criteria. Results indicate that 56% of OTs were detected before the time of a severe weather report (not shown). An OT detection preceded a NOAA National Weather Service severe weather warning for 35% of all OT-severe weather co-locations and could have provided 13-min additional warning lead time to forecasters. (not shown)

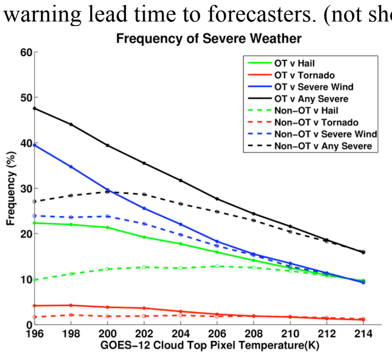

FIG 5: The relationship between OT detection pixels, non-OT cold cloud pixels, and severe weather with decreasing IRW BT.

c. Enhanced-V/Cold Ring Validation and Relationships With Severe Weather

Fig. 6 shows that an ensemble of storms can have numerous OT signatures but only a small subset of these storms feature the enhanced-V or cold-ring signature. The four V-signatures that occurred in these images were detected by the satellite algorithm and only these four storms produced severe weather (hail) within /- 30 mins of the image which featured at least 75 additional deep convective storms. Synthetic 2 km ABI enhanced-V/cold-ring detections have been processed for the 196 aforementioned MODIS and AVHRR scenes. The results show a detection POD of 53% and FAR of 24%. It was found that the OT signature was undetected for 15% of these events, which then inhibits V/ring signature detection. 76% of detected V/ring events were associated with severe weather versus 63% for undetected V/ring events, indicating that the satellite algorithm is focusing on the significant storms.

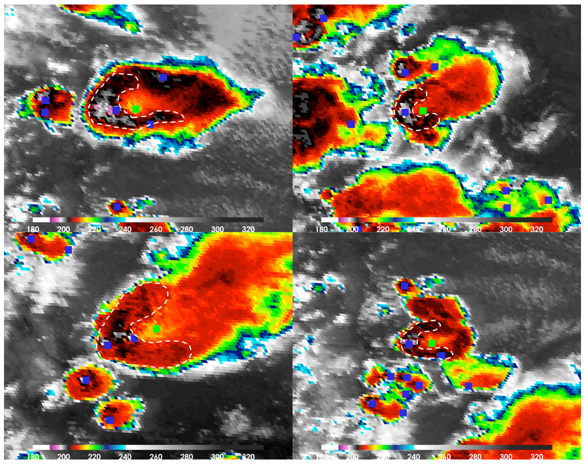
FIG 6: Examples of four OT and enhanced-V producing storms occurring in the lee of the Rocky Mountains on 10 May 2004 at 2315 UTC. OT detections are identified by blue squares and V/ring detections are identified by green squares.

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IV. ACKNOWLEDGMENTS

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V. REFERENCES

Bedka, K. M., J. Brunner, R. Dworak, W. Feltz, J. Otkin, and T. Greenwald, 2010: Objective satellite-based overshooting top detection using infrared window channel brightness temperature gradients. *J. Appl. Meteor. And Climatol.*, **49**, 181-202.

Bedka, K. M., 2011: Overshooting cloud top detections using MSG SEVIRI infrared brightness temperatures and their relationship to severe weather over Europe. *Atmos. Res.*, **99**, 175-189.

Bedka, K. M., R. Dworak, J. Brunner, and W. Feltz, 2011: Validation of satellite-based objective overshooting cloud top detection methods using CloudSat Cloud Profiling Radar observations. Submitted to *J. Appl. Meteor. And Climatol.*

Brunner, J. C., S. A. Ackerman, A. S. Bachmeier, and R. M. Rabin, 2007: A Quantitative Analysis of the enhanced-V feature in relation to severe weather. *Wea. Forecasting*, **22**, 853–872.

Dworak, R., J. Brunner, K. Bedka, and W. Feltz, 2011: Comparisons between GOES-12 overshooting top detections, WSR-88D radar reflectivity, and severe storm reports. Submitted to *Wea. Forecasting*.

Setvak, M, R. M. Rabin, P. K. Wang, 2007: Contribution of the MODIS instrument to observations of deep convective storms and stratospheric moisture detection in GOES and MSG imagery. *Atmos. Res.*, **83**, 505-518.