Validation of Satellite-Based Objective Overshooting Cloud-Top Detection Methods Using CloudSat Cloud Profiling Radar Observations

KRISTOPHER M. BEDKA
Science Systems and Applications, Inc., Hampton, Virginia

RICHARD DWORAK, JASON BRUNNER, AND WAYNE FELTZ
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin—Madison, Madison, Wisconsin

(Manuscript received 24 June 2011, in final form 1 March 2012)

ABSTRACT

Two satellite infrared-based overshooting convective cloud-top (OT) detection methods have recently been described in the literature: 1) the 11-μm infrared window channel texture (IRW texture) method, which uses IRW channel brightness temperature (BT) spatial gradients and thresholds, and 2) the water vapor minus IRW BT difference (WV-IRW BTD). While both methods show good performance in published case study examples, it is important to quantitatively validate these methods relative to overshooting top events across the globe. Unfortunately, no overshooting top database currently exists that could be used in such study. This study examines National Aeronautics and Space Administration CloudSat Cloud Profiling Radar data to develop an OT detection validation database that is used to evaluate the IRW-texture and WV-IRW BTD OT detection methods. CloudSat data were manually examined over a 1.5-yr period to identify cases in which the cloud top penetrates above the tropopause height defined by a numerical weather prediction model and the surrounding cirrus anvil cloud top, producing 111 confirmed overshooting top events. When applied to Moderate Resolution Imaging Spectroradiometer (MODIS)-based Geostationary Operational Environmental Satellite-R Series (GOES-R) Advanced Baseline Imager proxy data, the IRW-texture (WV-IRW BTD) method offered a 76% (96%) probability of OT detection (POD) and 16% (81%) false-alarm ratio. Case study examples show that WV-IRW BTD identifies much of the deep convective cloud top, while the IRW-texture method focuses only on regions with a spatial scale near that of commonly observed OTs. The POD decreases by 20% when IRW-texture is applied to current geostationary imager data, highlighting the importance of imager spatial resolution for observing and detecting OT regions.

1. Introduction and background

A new method for objective satellite-based overshooting cloud-top (OT) detection has been recently introduced (Bedka et al. 2010). This so-called infrared window channel texture (IRW texture) method uses a combination of 1) 11-μm infrared window (IRW) channel brightness temperatures (BTs) and their spatial gradients, 2) a numerical weather prediction (NWP) model tropopause temperature forecast, and 3) OT size and BT criteria defined through analysis of 450 thunderstorm events within 1-km Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) imagery to identify clusters of pixels significantly colder than the surrounding anvil cloud with a diameter consistent with commonly observed OTs. The IRW-texture method has been demonstrated with synthetic 2-km Geostationary Observing Environmental Satellite-R Series (GOES-R) Advanced Baseline Imager (ABI) data generated through 1) degradation of 1-km MODIS IRW BT data to the ABI navigation-resolution and 2) cloud resolving NWP model output coupled with a forward radiative transfer model. The IRW-texture method has also been applied to data from other imagers such as GOES-J2 and Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI; Schmetz et al. 2002) and multiyear databases of OT detections have been produced over the eastern United States and continental Europe. These OT
detection databases were gridded and separated by time of day to show the regions that are most often impacted by significant convective storms and to illustrate diurnal variability in convective storm activity (Bedka et al. 2010; Bedka 2011). Aviation turbulence and cloud-to-ground lightning were found to be concentrated near the OT region (Bedka et al. 2010). The OT databases were recently compared with severe weather reports over Europe and the continental United States (Bedka 2011; Dworak et al. 2012). An OT was detected within a storm that produced damaging wind or large hail for ~50% of these severe weather events, though many other OTs were detected within nonsevere storms or storms where severe weather was unreported. The results of Dworak et al. (2012) suggest that OT detections can help to increase severe weather warning lead time especially in the absence of reliable weather radar data.

Within the Bedka et al. (2010) study, the output from IRW-texture was compared with an alternative OT detection method based on the difference between the 6–7-μm water vapor absorption and ~11-μm IRW channel BTs (WV-IRW BTD; Schmetz et al. 1997; Setvak et al. 2007 and references therein). The premise behind the use of the WV-IRW BTD for OT detection is that 1) the atmospheric temperature profile warms with height in the lower stratosphere, 2) water vapor is forced into the lower stratosphere at levels above the physical cloud top by the overshooting storm updraft, 3) this water vapor emits at the warmer stratospheric temperature whereas emission in the IR window channel originates from the colder physical cloud top, and 4) positive differences between the warmer WV and colder IRW BTs can therefore identify where overshooting is occurring. The maximum WV-IRW BTD can be offset from the OT location because of advection of stratospheric water vapor away from the active thunderstorm updraft (Setvak et al. 2007) or from other remote sources not related to overshooting convection. The literature suggests that a BTD value of +2 K is shown to indicate the presence of an OT in MODIS and GOES-R ABI imagery (see Bedka et al. 2010 and references therein). The WV-IRW BTD was determined to have value especially for small convective clouds with limited (i.e., ≤15 km) anvil horizontal extent, but the IRW-texture method was found to provide a more consistent day–night OT detection capability, allowing for unambiguous interpretation and application of IRW-texture product output for aviation and severe weather forecasting.

To reach this conclusion, Bedka et al. (2010) produced qualitative and quantitative comparisons of OT detection output from these two methods with “truth” OT locations inferred from a variety of datasets. Detection output was compared with OT signatures in 0.25-km visible channel imagery from the MODIS instrument aboard the National Aeronautics and Space Administration (NASA) Aqua satellite. Algorithm performance was also demonstrated through comparison with a single OT event observed by the NASA CloudSat satellite. Aqua and CloudSat represent two components of the NASA A-Train satellite constellation (Stephens et al. 2002). As an OT can exist for only a period of minutes and often has a diameter of ≤15 km, OT events are not often observed by vertical profiling instruments such as CloudSat so considerable manual and subjective investigation is necessary to obtain a large “truth” OT sample size. The time required for such an effort was prohibitive at the time of the Bedka et al. (2010) study.

A quantitative estimate of ABI IRW-texture and WV-IRW BTD OT detection accuracy was derived by Bedka et al. (2010) through comparison of product output with OTs identified within cloud resolving Weather Research and Forecasting (WRF) NWP model output. The WRF OT locations were associated with cloud tops above the tropopause and anomalously large lower-stratospheric ice hydrometer mixing ratios. This comparison showed that the IRW-texture method false-alarm ratio (FAR) ranges from 4.2% to 38.8%, depending upon the overshoot magnitude and algorithm quality control settings. The overshoot magnitude was defined as the difference between the OT peak height and the mean height of the surrounding anvil cloud, which generally resides near the equilibrium level. The results also show that this method offers an improvement over the WV-IRW BTD technique, which featured an FAR of 2.3% to 46.1% and a lower probability of OT pixel detection. While this validation method provided some concept of the relative accuracy of the two techniques, the ABI satellite imagery and inferred OT locations are entirely based on an NWP-simulated environment for a single storm outbreak, which may not be truly representative of OTs that occur in nature or those present on another day with a differing thermodynamic environment.

A clear understanding of the quantitative accuracy of OT detection methods is very important because objective OT detection is a required product for the GOES-R ABI satellite program (Schmit et al. 2005; Feltz et al. 2008). A product accuracy metric must be met before an algorithm is deemed acceptable for future operations within the ABI program; the FAR for the GOES-R overshooting top detection algorithm cannot exceed 25%. Unfortunately, a database that lists the locations of all OTs present within each and every satellite image does not currently exist. This has necessitated the development of an OT validation database that can be used to contribute to estimating the accuracy of the future ABI OT detection algorithm.
This paper describes the validation of the IRW-texture and WV-IRW BTD detection methods using an OT database developed from analysis of 1.5 years of CloudSat observations. During this 1.5-yr period, 111 CloudSat-observed OT events were found through manual analysis of nearly 3000 CloudSat orbits. Synthetic ABI data, produced through degradation of 1-km Aqua MODIS data to the 2-km ABI spatial resolution (at nadir) and navigation serves as the primary input to these two OT detection methods. The IRW-texture and WV-IRW BTD methods are being considered as candidate methods for operational OT detection within the GOES-R ABI program. The ABI is currently scheduled for launch in 2016. CloudSat and Aqua MODIS observe the Earth’s atmosphere within a maximum of two minutes of each other, offering a rare opportunity to precisely collocate infrared-based OT detection output with confirmed OT events. The ABI OT detection accuracy is compared with that derived from many of the current geostationary satellite imagers to demonstrate the improvement in detection capability that will be offered via the improved spatial resolution of the ABI.

Section 2 of this paper describes the datasets and methodology used in this study. Section 3 discusses the primary results. Section 4 summarizes the study and offers suggestions for future work on this topic.

2. Datasets and methodology

a. CloudSat overshooting top observations

The CloudSat Cloud Profiling Radar (CPR) reflectivity factor product (2B-GEOPROF; Stephens et al. 2002; Mace et al. 2007) is used to identify OT events during the April 2008 to September 2009 time period. The footprint of a CloudSat CPR profile covers 1.7 km in the along-track direction and 1.3 km in the across-track direction. A new profile is captured every 1.1 km, indicating that there is some overlap between adjacent profiles (i.e., oversampling). The effective vertical resolution is 480 m, with oversampling at a 240-m resolution. The 2B-GEOPROF product provides a cloud mask and radar reflectivity at each of the 125 vertical data bins. Each vertical bin is assigned with a one bit mask: 0 for no cloud detected; 1 for likely bad data; 5 for likely ground clutter; 6–10 for weak echo detected from along-track integration; 20–40 for cloud detected. Because larger values represent less probability of a false detection, we use mask values of 20–40 for the cloud identification. See the CloudSat Data Products Handbook (http://cloudsat.cira.colostate.edu/cloudsat_documentation/CloudSat_Data_Users_Handbook.pdf) for an additional description of CloudSat and the 2B-GEOPROF product.

Possible CloudSat OT observations are identified through subjective analysis of archived 2B-GEOPROF quick-look imagery available on the Colorado State University CloudSat Data Processing Center (DPC) web page (http://www.cloudsat.cira.colostate.edu/). Imagery from nearly 3000 CloudSat orbits was investigated over the 1.5-yr study period. After the list of possible OT events is developed, the 2B-GEOPROF product for these events is acquired from the CloudSat DPC and each possible event is carefully analyzed to verify the presence of a protrusion above an NWP tropopause height analysis and the surrounding anvil cloud top, which is consistent with a conceptual model of an OT (Adler and Mack 1986; Wang 2003). The Goddard Earth Observing System Model, version 5 (GEOS-5; http://gmao.gsfc.nasa.gov/systems/geos5/), tropopause height contained within Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) level-2 1-km cloud layer data files is used here. The highest cloud top must be at least 0.5 km (i.e., 2 CloudSat vertical data bins) above the surrounding anvil cloud for two adjacent CloudSat profiles to ensure the presence of a coherent OT signature. This implies that the smallest OT in the final OT database can be ~2.8 km in diameter in the along-track direction. For daytime events, Aqua MODIS 250-m spatial resolution visible imagery along the CloudSat overpass is also analyzed to further verify that CloudSat observed an OT. The OT events that meet these criteria are assigned to the final OT database. A total of 111 OT events were found during the April 2008 to September 2009 study period: a list of day, time, and latitude/longitude coordinates for these events can be found at http://angler.larc.nasa.gov/site/people/data/kbedka/Bedkaetal_JAMC2012/April2008-Sept2009_CloudSat_OTevents.pdf.

It is important to note that Aqua MODIS collects observations approximately two minutes ahead of CloudSat. As OTs are often rapidly evolving phenomena, this can lead to some mismatch between the cloud-top characteristics observed by MODIS and CloudSat. Examination of 1-min GOES Super Rapid Scan observations of deep convection by the authors of this paper (see the following for an example: http://cimss.ssec.wisc.edu/goes/blog/wp-content/uploads/2010/09/100921_g15_srso_vis_overshoots_anim.gif) indicates that the typical lifetime of an OT is less than 5 min. An OT detected via MODIS satellite imagery could weaken by the time it is observed by CloudSat and the detection would be considered a false alarm. The converse of this would be that a new OT could form after the satellite scan, reducing the probability of detection of the satellite algorithm. The OT detection validation method in this paper attempts
to account for the time difference and this will be described in the following section.

Cloud-top height retrievals from the CALIOP would also seem to be a useful dataset to study the height characteristics of OTs and anvil cirrus clouds. CALIPSO, CALIOP is a component of the A-Train constellation that can also be precisely collocated with Aqua MODIS observations. CALIOP data has been investigated for a sample of CloudSat-observed OT events and it was discovered that the current 0.33- and 1-km-spatial-resolution version-2 CALIOP cloud-top height retrieval algorithm often fails for optically thick convective clouds with heights significantly higher than the tropopause. A solution for this issue is currently under development (M. Vaughan, NASA Langley Research Center, 2009, personal communication). The CALIOP level-1 lidar backscatter field could also be investigated, as it is valid throughout the troposphere and lower stratosphere. If one were to review a large data volume of backscatter data via quick-look imagery in an effort to screen for possible OT events, it would be challenging to differentiate high, thick cirrus cloud exhibiting some vertical variability from deep convective overshooting tops because signal is only returned from the upper surface of the cloud and one cannot visualize the full cloud vertical structure. The CloudSat CPR provides detailed vertical cloud structure information, allowing one to easily make this differentiation. The authors feel that use of CALIOP data could help to further confirm or deny the presence of overshooting, but it likely would not help to identify a significant number of additional OT events. An investigation of the relationships between CALIOP, CloudSat, and MODIS OT signatures is described by Setvak et al. (2012).

b. Satellite imager data and colocation with CloudSat observations

MODIS data from the NASA Aqua satellite are acquired from the NASA Level 1 and Atmosphere Archive and Distribution System (LAADS) for each of the events within the CloudSat OT database. The 1-km MODIS infrared BTs are degraded in resolution and reprojected to emulate how an OT would appear in ABI imagery if the ABI were positioned at the location of the nearest of today’s existing geostationary satellites. Table 1 provides a list of subsatellite points for each of the current geostationary satellites considered in this study. Synthetic ABI IRW BT imagery and Global Data Assimilation System (GDAS; Kanamitsu (1989)) tropopause temperature information are used as input to the IRW-texture OT detection algorithm. See Bedka et al. (2010) for a detailed IRW-texture algorithm description. WV absorption channel BTs are also used here to compute the WV-IRW BTD. An Interactive Data Language (IDL) routine from L. Gumley [University of Wisconsin Space Science and Engineering Center (UW-SSEC), 2010, personal communication] was used to remove line-to-line inconsistencies (i.e., “stripes”) that are evident in the LAADS MODIS level-1B WV channel radiance field. While this des triping routine is not perfect, it offers a significant improvement over the original WV BT field. To further mitigate the impact of striping on these results, the WV-IRW BTD was averaged over a 3 × 3 pixel region and this mean BTD is applied to the center pixel of the box, similar to the approach described by Chung et al. (2008). OT detections based on mean BTD values ranging from 0 to 4 + K are collocated with the CloudSat overpass and validated in this study.

All synthetic ABI data, including IRW-texture and WV-IRW BTD–based OT detections, are then collocated with the CloudSat overpass using the MODIS “MYD03” 1-km navigation and the “MAC03” MODISCloudSat colocation products. These navigation and collocation products were acquired from the LAADS and the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC), respectively. The true Earth-relative location of deep convective clouds can differ by 3–5 km from the MODIS-observed cloud location because of parallax (Setvak et al. 2010). The synthetic ABI IRW-texture OT pixel detection locations were not explicitly corrected for parallax, but this will not affect the validation results because a pixel is still considered an accurate detection if it is within a small distance from the CloudSat OT location (see the following section for description).

The OT detections are also derived using data from GOES-11, GOES-12, Meteorological Satellite-9 (Meteosat-9) SEVIRI, and the Multifunction Transport Satellite (MTSAT-2) for the CloudSat-observed OT events viewed by these satellites. The imagery from these instruments was acquired from UW-SSEC via Man Computer Interactive Data Access System (McIDAS-X; Lazzara et al. 1999). The OT algorithm could not process Meteosat-7 OT events because the data from this satellite could not be converted into the necessary data format at the time of validation.
this publication. OT events observed by current geostationary imagers are processed if the image time stamp is \( \pm 5 \) min from the time of the CloudSat OT observation. The image time stamp in corresponds to the time of the first image scan line when the data are acquired via McIDAS-X, so the actual time difference between the CloudSat profile and the satellite imagery can approach 20 min, depending on satellite scan strategy. Because of this time difference and coarser spatial resolution relative to the ABI, one should expect some differences in OT detection characteristics when these images are used and the validation results should be considered a rough estimate of the geostationary imager detection capability. Detections are parallax corrected based on a constant 16-km height since pixel location errors in geostationary imagery can be greater than 20 km for deep convective clouds at large satellite viewing angles. OT detections are then collocated with the CloudSat overpass and validated using the method described below. The accuracy of the WV-IRW BTD method is not evaluated for these instruments.
c. Overshooting top detection validation

In the statistical validation component of this study, CloudSat-observed OTs are treated as both single coherent entities (i.e., “OT regions”) and as the individual pixels that compose the top. This distinction is important because a detection method may not identify every pixel within an OT along the CloudSat track but could identify some portion of the OT region. If some portion of the OT region is detected, this should be rewarded within the validation framework. The exact location and spatial extent of an OT is subjectively determined through examination of the CloudSat 2B-GEOPROF profile (Fig. 1). OT detection results are validated along the entire CloudSat overpass within each of the 105 MODIS scenes. A large number of deep convective cloud pixels were collocated with CloudSat within each of these scenes, providing an adequate sample size to demonstrate the algorithm’s skill in discriminating OT regions from ordinary convective cloud tops. An attempt was made to match the domains processed for events observed by current geostationary imagers to the domain observed by the corresponding MODIS granule.

The following metrics are used to evaluate the accuracy of IRW-texture and WV-IRW BTD OT detections: 1) OT pixel FAR and 2) probability of detection (POD) of all possible OT regions. An OT pixel POD cannot be accurately determined here because either detection method would be penalized if the storms moved in the 2-min time interval between the satellite imager and CloudSat observations and the OT detections did not match all CloudSat-observed OT fields of view. The FAR for OT regions cannot be computed for the WV-IRW BTD method since this method is entirely pixel
based and does not survey the anvil spatially to group pixels into OT regions. Therefore, this metric is omitted here to maintain consistency in validating both OT detection techniques.

The OT pixel detections are considered accurate if they are found within a region extending to 5 km outside the bounds of the CloudSat-observed OT. The distance window outside the OT is used here to account for storm movement–evolution in this 2-min time interval, parallax correction error, and other possible navigation- and/or collocation-induced errors. The OT pixel FAR is defined as

\[
\text{OT Pixel FAR} = \frac{\text{Number of incorrect OT pixel detections}}{\text{Total number of OT pixel detections}}.
\]

An OT region is accurately detected if at least one synthetic ABI detection pixel is found within the bounds of the CloudSat-observed OT region. The POD for all possible tops is defined as

\[
\text{OT Region POD} = \frac{\text{Total number of accurately detected OT regions}}{\text{Total number of CloudSat observed OT regions}}.
\]

3. Results

This section begins with a discussion of two CloudSat-observed OT events and the associated OT detection fields. Figure 1 shows a deep convective cloud over the South Pacific Ocean that features a classic example of an OT, where a sharp BT minima and a lumpy appearance in the visible channel image is collocated with a significant OT signature in the CloudSat CPR profile. The diameter of this OT is 14.5 km, which is quite large relative to other OTs in the CloudSat database and those within the 450 thunderstorm events described by Bedka et al. (2010).

The MODIS imagery for the Sudan OT case shown in Fig. 2 shows very similar patterns to that of Fig. 1, though the minimum IRW BT is much colder because of a higher tropopause level. The OT-anvil IRW BT

![Fig. 3. (a) IRW-texture OT detections and (b) WV-IR BTD = 0 K for the 9 May 2008 case shown in Fig. 1. Colored BTD values are defined in the color bar at the top of the panel. (c),(d) As in (a) and (b) but for the 9 Oct 2008 case shown in Fig. 2.

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difference is 14.8 K for this case, but the overshoot magnitude is only 0.75 km, yielding an unprecedented 19.7 K km\(^{-1}\) lapse rate. As a lapse rate of this magnitude is virtually impossible, the authors suspect that this was either caused by parallax or that the OT was not prominent in IRW imagery but then developed by the time that the CloudSat CPR profile was collected nearly 2 min later. The likelihood of such a mismatch increases with increasing time interval between the CloudSat and corresponding IRW satellite imagery. Such scenarios can impact the following quantitative validation results so care must be taken in the interpretation of these statistics, especially for the current geostationary OT comparisons where the time interval between observations can approach 20 min.

Figures 3a,c show that IRW-texture method identified both the CloudSat-observed OTs shown in Figs. 1 and 2. Several other regions were detected that correspond with the typical OT signature in visible channel imagery (see lower-left panels of Figs. 1 and 2). The transect shown in the middle panels of Figs. 1 and 2 indicates that the WV-IRW BTD peaked within the OT region at 2.1 K for the South Pacific case and over 5 K for the Sudan case. Positive BTD values are found throughout the entire anvil cloud outside of the OT regions. This is consistent with the results shown by Bedka et al. (2010), indicating that significant false alarm occurs when BTD ≥ 0 K is used for OT detection. Though a state-of-the-art destriping algorithm was applied to the WV channel imagery, some degree of striping is still evident in the BTD plots shown in Figs. 3b,d. Anomalously large WV-IRW BTD values are evident in the stripes in these examples. Therefore it is likely that some percentage of the false alarm in subsequent quantitative validation results can be attributed to striping, though it is not possible to determine the exact distribution between “good” data and errant striped data that are included in this study.

The OTs were most often observed by CloudSat over the tropics during the time period of this study (Fig. 4). Only 11 of the 111 total OTs (10%) were found in the midlatitudes. The Aqua satellite has an equatorial crossing time of 0130/1330 local standard time, which does not coincide with the time period where deep convection is most often present in the midlatitudes. OTs were found more often in the Northern Hemisphere because the 1.5-yr study period covers two Northern Hemisphere warm seasons, but only one for the Southern Hemisphere. Figure 4 also shows that the CloudSat-observed OTs were better detected over land regions, such as Africa and South and North America, than those occurring over water. Heymsfield et al. (2010) shows that the maximum upward vertical motion in land-based convection is of greater magnitude and at a higher vertical level than convection over ocean. Thus, OTs over land would likely be of larger magnitude and would therefore appear more prominently in IRW imagery, leading to a higher detection rate using the IRW-texture method.

Validation statistics for the IRW-texture and WV-IRW BTD detection methods are shown in Table 2. The
IRW-texture method detected 75.6% of the OT regions and 17.6% of the 940 total OT detection pixels were considered false detections. The IRW-texture method meets the GOES-R operational algorithm accuracy requirement of 25% maximum FAR. Various WV-IRW BTD thresholds are evaluated here to determine if BTD magnitude can be used to increase detection performance to a level comparable with that of IRW-texture. The results show that both the pixel FAR and OT region POD steadily decrease with increasing BTD. A positive WV-IRW BTD value can be used to identify nearly all OT regions, but it is apparent that the vast majority of pixels that meet this BTD threshold are false detections. A BTD of $\approx 2 \text{ K}$ is required for the WV-IRW BTD POD to be equivalent to that from the IRW-texture method, but the pixel FAR for this BTD criterion (56%) would far exceed the IRW-texture FAR.

Analysis indicates that 17 of the 28 (−61%) undetected IRW-texture OTs did not have cloud tops colder than the GDAS tropopause temperature, so these OT regions were never considered by IRW-texture (not shown). Based on this information, one might infer that the use of NWP tropopause information is adversely affecting algorithm OT detection performance. To test this, a version of IRW-texture method that does not require an OT pixel to have an IRW temperature below that of the tropopause was applied to the 105 synthetic ABI IRW BT datasets. Table 2 shows that the OT region POD does increase when the GDAS tropopause temperature check is removed, but the FAR also increases significantly. Figure 5 shows the CloudSat CPR profile and MODIS imagery for an event where false OT detections were produced after removal of the tropopause temperature check. Figure 6 shows that the number of OT detections increases from 4 to 19 when this check is removed for this
event. Analysis of MODIS imagery for these OT locations indicates that many of these additional detections correspond with IRW BT minima and enhanced visible channel texture, which are signatures typically associated with OTs. At 268 latitude, the CloudSat CPR profile shows an overshooting magnitude of 0.25 km, which is less than the 0.5-km requirement used to identify cases for the CloudSat OT validation database. This apparently weak magnitude could be attributed to the CloudSat profile not sampling region of peak OT height detected by MODIS, decay of the OT region within the 2-min time difference between the two datasets, and/or parallax.

Based on this example, it is possible that some component of the additional FAR is caused by detection of marginal OTs that did not meet our vertical magnitude criteria. The OT detections present along the CloudSat overpass at −7.4° latitude illustrates that removal of the tropopause temperature check also causes legitimate false OT detection, as convective cirrus clouds can have spatially complex BT patterns that may appear similar to an OT within the IRW-texture framework. These results indicate that use of the NWP tropopause temperature information in the IRW texture method greatly minimizes false detection while preserving detection of a significant majority of OT events.

IRW-texture OT detections using IRW imagery from GOES-11, GOES-12, Meteosat-9 SEVIRI, and MTSAT have also been produced and compared with the CloudSat OT database. The purpose of this comparison is to document the accuracy of this method for current generation imagers for comparison with the synthetic ABI-based validation statistics. Table 3 shows that the synthetic ABI pixel FAR is comparable to that from current geostationary data but the ABI OT region POD is ~20% better. Geostationary imager spatial resolution has a significant impact on these results being that high-resolution data are required to observe the small regions of very cold IRW BTs present in OTs. A comparison between time-matched 4-km GOES-12 and 1-km AVHRR–MODIS IRW imagery for a random subset of the 450 storms described by Bedka et al. (2010) indicates that the minimum OT IRW BT was on average 12 K colder in AVHRR–MODIS imagery (not shown). Therefore, current GOES may not be observing BTs that are both colder than the tropopause and significantly colder than the anvil cloud, which reduces the GOES and other current geostationary imager OT detection capabilities. The 3-km resolution of SEVIRI falls in between that of current GOES and the synthetic ABI and so does the OT region POD for this instrument. The pixel FAR for SEVIRI is much higher than that of GOES, caused by an abundance of relatively small deep tropical convective storms across Africa, which can trigger false alarms when storms of varying BT characteristics are very close to one another. The relatively low POD for MTSAT can be attributed to the 5-km MTSAT spatial resolution coupled with the fact that, in many of these events, MTSAT did not observe IRW BTs colder than the NWP tropopause temperature. Over the MTSAT domain, 33% (68%) of OTs were detected with 5-km MTSAT (2-km synthetic ABI). A larger sample size of OT detection pixels and higher temporal resolution imagery are required to draw definitive conclusions on the reasoning behind differing detection performance between current geostationary instruments.

### Table 3. Validation statistics for the IRW-texture OT detection method applied to current geostationary imager data for cases in which the image time stamp was ±5 min from the CloudSat OT observation.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>OT pixel FAR (%)</th>
<th>POD for OT regions (%)</th>
<th>No. of OT detection pixels along CloudSat track</th>
<th>No. of obs CloudSat OT events</th>
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</thead>
<tbody>
<tr>
<td>GOES-11 and GOES-12</td>
<td>10.0</td>
<td>46.2</td>
<td>90</td>
<td>26</td>
</tr>
<tr>
<td>Meteosat-9</td>
<td>22.8</td>
<td>64.7</td>
<td>162</td>
<td>34</td>
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<tr>
<td>MTSAT</td>
<td>9.1</td>
<td>33.3</td>
<td>33</td>
<td>12</td>
</tr>
<tr>
<td>All current geostationary satellites</td>
<td>17.2</td>
<td>55.2</td>
<td>265</td>
<td>72</td>
</tr>
</tbody>
</table>
4. Summary

This study evaluates the OT detection accuracy of the IRW-texture and WV-IRW BTD methods relative to a database of 111 OT events identified through manual analysis of nearly 3000 CloudSat CPR orbits from April 2008 to September 2009. CloudSat OT events must have an overshooting magnitude of at least 0.5 and $\geq 2.8 \text{ km}$ in horizontal extent to be part of this database. Qualitative analysis of detection characteristics for two OT events occurring over the South Pacific and Sudan indicate that IRW-texture detections were isolated to regions exhibiting the characteristic OT signature in visible channel imagery, while WV-IRW BTD values $\geq 0 \text{ K}$ covered much of the deep convective anvil cirrus cloud. Local WV-IRW BTD maxima were collocated with CloudSat-observed OTs, but the BTD magnitude at the OT location differed by $3 \text{ K}$ between the two events, indicating that a useful BTD threshold for OT detection can vary significantly.

When MODIS-based synthetic GOES-R ABI imagery is used as input to the two detection methods, validation statistics show that the OT region POD for the WV-IRW BTD $\geq 0 \text{ K}$ threshold was 17% better than the IRW-texture method but the OT pixel detection FAR was 63% worse for the BTD method. A BTD value $\geq 2 \text{ K}$ is required to match the $\sim 76\%$ IRW-texture POD, but the FAR would still be 38% higher at this BTD value. These results also show that the IRW-texture algorithm requirement that a pixel IRW BT must be at or colder than the NWP tropopause causes a 17% POD reduction. The FAR increases significantly when this check is removed, but qualitative analysis suggests that a component of this increased FAR may be caused by detection of marginal ($\leq 0.5\text{-km magnitude}$) OT events that are not represented in the CloudSat OT database. OTs over land were better detected than those over water, which is likely because the maximum upward vertical motion in land-based convection is of greater magnitude and at a higher vertical level than convection over ocean, producing OT signatures that are more prominent in IRW imagery.

Imagery from current generation geostationary imagers was used as input to the IRW-texture method to investigate OT detection performance, with the understanding that the validation statistics will be impacted by the 20-min time difference between the imagery and CloudSat OT observation and the coarser spatial resolution of current data relative to the GOES-R ABI proxy comparisons. The results show that the FAR is quite comparable between current and synthetic future generation geostationary imagery, but the POD decreases by $\sim 20\%$. POD was correlated with the imager spatial resolution with MSG SEVIRI (MTSAT) having the highest (lowest) POD. Over the MTSAT domain, 33% (68%) of OTs were detected with $\sim 5\text{-km MTSAT}$ ($\sim 2\text{-km}$ synthetic ABI). The primary reason for failed MTSAT detections was the fact that MTSAT IRW temperatures were often not colder than the NWP tropopause temperature, caused in part by the relatively coarse MTSAT spatial resolution. A larger sample size of OT events and higher temporal resolution imagery are required to draw definitive conclusions on the reasoning behind differing detection performance between instruments.

The results shown here coupled with those from other previous studies on the WV-IRW BTD method suggest that WV-IRW BTD and IRW-texture can be used in combination to form an objective product that identifies deep convective clouds and the locations of penetrative updrafts within these clouds. Future work will be directed toward improving detection performance for current generation geostationary instruments using seasonally and regionally varying detection thresholds. An OT validation database using ground-based weather radar OT inferences will also be developed that would provide a significant increase in sample size and greater insight into algorithm detection characteristics. A database of OT signatures subjectively identified by a human analyst via texture and shadow cast upon the surrounding anvil within visible channel imagery could also be developed and used to validate OT detections.

Acknowledgments. The authors thank the UW-SSEC McIDAS-V development team for providing support for the MODIS and overshooting top detection datasets used to create the figures in this paper. This work was supported in part by funding from the NASA Applied Sciences Program and the GOES-R Algorithm Working Group.

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