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# Contribution of the MODIS instrument to observations of deep convective storms and stratospheric moisture detection in GOES and MSG imagery

Martin Setvák<sup>a,\*</sup>, Robert M. Rabin<sup>b</sup>, Pao K. Wang<sup>c</sup>

<sup>a</sup> CHMI, Satellite Department, Na Šabatce 17, CZ-14306 Praha 4, Czech Republic
<sup>b</sup> NOAA/National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069, USA
<sup>c</sup> University of Wisconsin-Madison, 1225 W. Dayton Street, Madison, WI 53706, USA

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#### Abstract

Past studies based on the NOAA/AVHRR and GOES I-M imager instruments have documented the link between certain storm top features referred to as the "cold-U/V" shape in the  $10-12 \mu m$  IR band imagery and plumes of increased 3.7/3.9  $\mu m$  band reflectivity. Later, similar features in the 3.7/3.9  $\mu m$  band have been documented in the AVHRR/3 1.6  $\mu m$  band imagery.

The present work focuses on storm top observations utilizing the MODIS data. The MODIS instrument (available onboard NASA's EOS Terra and Aqua satellites) provides image data with significantly better geometrical resolution (in some of its bands) and broader range of spectral bands as compared to that from AVHRR/3 observations. One of the goals of this study is to evaluate the contribution of this new instrument to observations of convective storm tops. Besides the cloud top features linked to storm top microphysics and morphology, the paper also addresses the possibility of detection of lower stratospheric water vapor above cold convective storm tops. This issue is explored utilizing MODIS as well as GOES and MSG imagery.

In addition, the paper discusses an alternative interpretation of the "cold-U/V" patterns at the top of intense storms by a mechanism of "plume masking" as suggested by some of the observations.

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# 1. Introduction

This paper further investigates the topics addressed in Setvák et al. (2003): the appearance of cloud tops of deep convective storms in various NOAA/AVHRR and GOES-8 and 9 spectral bands (for all abbreviations used in this paper please refer to the *List of abbreviations* at the end of the paper), namely features

\* Corresponding author. Fax: +420 24403 2442. *E-mail address:* setvak@chmi.cz (M. Setvák). related to cloud top microphysics. Among various features observed at or above anvil tops of deep convective storms, the most interesting ones are those referred to as "plumes" (Setvák and Doswell, 1991; Levizzani and Setvák, 1996). Though first revealed in the AVHRR 3.7  $\mu$ m band (due to their higher reflectivity in this band), plumes can be found also in all visible (VIS) or near IR (NIR, here the range of spectrum approximately between 0.7 and 5  $\mu$ m) bands. While the majority of studies reporting plumes date back to the second half of 80's through the mid-

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90's, this topic has become of interest again due to progress in several research areas:

- modeling of radiative (scattering) properties of nonspherical ice particles within plumes above tops of convective storm anvils (Melani et al., 2003);
- 3D-modeling of deep convective storms, showing moisture plume formation, with related possible impacts on cross-tropopause moisture transport (Wang, 2003; Weber and Doswell, personal communication — Dec 2002);
- cross-tropopause water vapor transport generated by deep convective clouds in general (i.e. not restricted to plumes only), namely those observed by geostationary and polar-orbiting weather satellites (Schmetz et al., 1997; Fritz and Laszlo, 1993).

Moreover, the availability of several new NIR spectral bands on the MODIS instrument of the NASA's EOS Terra and Aqua satellites (King et al., 1992) and the SEVIRI instrument of the EUMETSAT's MSG satellites (Schmetz et al., 2002), has recently initiated



Fig. 1. Storms above north Texas, Oklahoma and Kansas on 04 June 2002, 1730 UTC, MODIS Terra. A – An overall view of storms in VIS, NIR and IR bands, and the brightness temperature difference (BTD) product. B – The same as (A), but magnified over the two southernmost storms. C – The same storms as in (B), but with 250 m resolution, band 1. For details and comments see the text.

![](_page_2_Figure_2.jpeg)

Fig. 1 (continued).

new studies on the retrieval of cloud top properties and on the depth of the cloud top layer, which contributes to the appearance of cloud tops in these bands (Rosenfeld et al., 2002). Setvák et al. (2003) have documented a similar appearance of storm tops in the 1.6 and 3.9  $\mu$ m bands utilizing simultaneous observations from two different satellites (1.6  $\mu$ m band of NOAA 16, and 3.9  $\mu$ m bands of GOES-8 and GOES-10). The MODIS instrument (flown on the Terra satellite since 1999 and the Aqua satellite since 2002) has enabled to study the cloud top properties in these NIR spectral bands simultaneously, from one single satellite. With the MSG-1 launch in 2002, this has become available from geostationary observations. Naturally, these new instruments also provide an opportunity for more detailed observations of plumes and to address the previously mentioned research issues.

This study focuses on two individual cases of plumes above deep convective storms as seen in various bands of the MODIS data. The first of these cases, 04 June 2002, shows storms above northern Texas, Oklahoma and south Kansas, U.S.A. (Figs. 1 and 2). Besides investigating the appearance of these storms in the MODIS/Terra data, we also use this case to explore the evolution of lower stratospheric moisture as inferred from the brightness temperature differences (BTD) С

![](_page_3_Picture_3.jpeg)

Fig. 1 (continued).

between the water vapor and IR window channels of GOES-8 satellite. The second case, 13 June 2003, shows storms over Bavaria (Germany), south Bohemia (Czech Republic) and north Austria (Figs. 3 and 4). In this case, the appearance of storm tops is investigated in detail from MODIS/Aqua data, and the lower stratospheric moisture is inferred from BTD of MSG-1 SEVIRI data.

Besides the two cases mentioned above, the paper briefly summarizes a study of occurrence of plumes in various geographic regions based on MODIS data.

For description of spectral bands of the MODIS, GOES imager and SEVIRI discussed throughout this paper, refer to Tables 1, 2 and 3.

# 2. Data sources and processing

All the MODIS Terra and Aqua datasets discussed in this paper have been selected from the NASA's GSFC web site *MODIS Atmosphere* (http://modisatmos.gsfc.nasa.gov/IMAGES/). The selected MODIS Level-1B data sets were ordered and downloaded from the NASA's *DAAC Data Search and Order* site (http:// eosdata.gsfc.nasa.gov/data/). From a total of about 80 five-minute data granules showing deep convective storms over Europe and the eastern and central U.S. (Terra: April–August 2000–2002 and April–July 2003; Aqua: September 2002 and April–July 2003) only 9 data sets were found to show storms exhibiting plumes of various extents. Two of these are presented in this paper. Besides Europe and the U.S., additional 125 MODIS data granules from the remainder of the World were examined for the entire year of 2003.

Downloaded Level-1B granules were processed and displayed using the *ENVI 4.0* software from the Research Systems Inc. (at CHMI), and with the *McIDAS* (version 2003) software, (Lazzara et al., 1999) at the NSSL and SSEC. Besides ENVI and McIDAS, two additional routines were used for data processing. For removing line-to-line inconsistencies (striping) in some of the MODIS L1B WV and IR image bands, an IDL routine from Liam Gumley was utilized (MODIS destriping algorithm, courtesy of Liam Gumley, Space Science and Engineering Center, University of Wisconsin-Madison). For calibration of the MODIS L1B WV and IR bands within ENVI, the add-in library "Modistools" from Alexander Shumilin was used (ScanEx, http://eostation. scanex.ru).

The GOES-8 and MSG-1 (also labeled as Meteosat-8) data were processed and displayed using the McIDAS software (GOES-8 data at NSSL and SSEC; MSG data at EUMETSAT). Final preparation of all of the images used in this paper was done using *Adobe Photoshop CS* software.

# 2.1. 04 June 2002

Plumes, given their properties (Setvák and Doswell, 1991; Levizzani and Setvák, 1996), provide an excellent "test target" for evaluation of MODIS capabilities to detect thin or small-scale clouds in its VIS and NIR bands. Fig. 1 shows storms on 04 June 2002 above northern Texas, Oklahoma and southern Kansas, U.S.A., at 1730 UTC. While Fig. 1A shows a large-scale appearance of the storm tops, Fig. 1B gives a higher resolution view of the two southernmost storms, both exhibiting plumes above their anvil tops. In both low and high resolution figures, the general appearance of storm tops in the individual NIR bands (6, 7 and 20) is similar to each other. All the VIS and NIR bands of Fig. 1B show the plumes well and in good detail. However, certain subtle but detectable differences of the shape and definition of plumes can be found between these NIR bands in Fig. 1B. While the band 6 (1.6  $\mu$ m) appearance of the plume above the northern storm is very close to that in band 1 (showing a narrow plume, originating at northwest side of the overshooting top), the band 20  $(3.7 \ \mu m)$  shows a broader plume, positioning its right edge more to the east, with the plume's source being much wider, at the lee of the overshooting top. Band 7  $(2.1 \ \mu m)$  shows the outline of the plume as being somewhere between the two other bands. The shape of the plume in band 20 is close to the shape of the warm area, found in the band 31 image at the same location. The fact that the plume appears most distinctly in the 3.7  $\mu$ m band can be explained by the findings of Rosenfeld et al. (2002) who showed that the radiance of the 3.7–3.9  $\mu$ m bands originates in a rather thin cloud top layer, while that at shorter wavelengths (1.6  $\mu$ m) has a significant contribution from deeper layers (depending on the ice particle size). While the 3.7  $\mu$ m band should benefit from this in showing thin plumes (they should appear more clearly in this band as compared to bands 6 and 7), there is also a disadvantage due to its lower resolution (original pixel size of the 3.7  $\mu$ m band is 1 × 1 km, while bands at 1.6 and 2.1  $\mu$ m are scanned at 0.5 × 0.5 km).

We also note that for the northern storm there is a distinct "backward curvature" of the downwind part of the plume, resembling a plume form referred to as a "fan" in one of the cases described in Levizzani and Setvák (1996).

The IR window band 31 and brightness temperature difference (BTD) of bands 27 and 31 for the images shown in Fig. 1A and B are discussed later in this paper.

Finally, Fig. 1C shows the same storms in their highest resolution available on MODIS (250 m pixel size). While the previous plume images show mostly smooth features with no details, the 250 m resolution image shows very fine details of both plumes. Very high resolution may be important when comparing plume observations and their modeled features (Wang, 2003). Besides the plumes, a distinct "spiral shaped" feature in the cloud top core of the northern storm can be seen here. This resembles a similar feature described in Adler et al. (1981) as a possible consequence of updraft rotation. However, the MODIS 250 m band 1 shows the spiral in greater detail than the lower resolution imagery available during the time of that study.

Figs. 2A and B show the evolution of the storms described above based on the GOES-8 imagery. The time of the Terra's overpass coincides with that of the last images of Fig. 2A and B. Interestingly, the plumes described above can be seen in the GOES-8 band 1 (VIS) images even at this reduced resolution. The images shown in Fig. 2B will be discussed later in this paper in the part addressing BTD issues.

![](_page_4_Figure_7.jpeg)

Fig. 2. Storms above north Texas, Oklahoma and Kansas on 04 June 2002, 1645–1730 UTC, GOES-8. A – Storms in VIS band. B – Mosaic of IR window band and BTD product.

![](_page_5_Figure_2.jpeg)

Fig. 2 (continued).

# 2.2. 13 June 2003

Figs. 3 and 4 show a cluster of storms developed on 13 June 2003 over Bavaria (Germany), southern Bohemia (Czech Republic), and northern Austria. The MODIS/Aqua images (Fig. 3) are from 1156 UTC whereas the SEVIRI/MSG-1 images (Fig. 4) show the period of 1100–1400 UTC.

The eastern most storm in Figs. 3 and 4 exhibits a well-defined "cold-V" shape in all IR bands, and has

![](_page_6_Figure_2.jpeg)

Fig. 3. Storms above south Bohemia (Czech Republic), Bavaria (Germany) and north Austria on 13 June 2003, 1155 UTC, MODIS Aqua. A - VIS and NIR spectral range bands. B - Color enhanced IR window band 31 (top); BTD (WV minus IR window bands, band 27–band 31) product (middle); RGB color composite image of bands 1, 7 and 5 scaled to band 1 resolution. C - Black and white enhanced IR window band 31, and sounding from Praha-Libus from 12 UTC.

![](_page_7_Figure_2.jpeg)

Fig. 3 (continued).

significantly higher NIR reflectivity for the entire period. Radar observations showed that it was very likely a supercell. At the time of Aqua overpass, the storm produced 5 cm hailstones. By coincidence, this storm was in the center of Aqua (1156 UTC) and NOAA-16 (1247 UTC) swaths, thus providing the best possible resolution of image data from the MODIS and AVHRR instruments.

![](_page_8_Figure_1.jpeg)

![](_page_8_Figure_2.jpeg)

Fig. 3A shows these storms as seen in band 1 (VIS) and in bands 7 and 20 (NIR). Unfortunately, band 6 data suffered from line-to-line inconsistencies and are not usable. As can be seen in both NIR bands, the storm over southern Bohemia had a significantly higher NIR reflectivity than all other storms in the region. The increased NIR reflectivity covered the whole anvil, and the enhancement was stronger in a form of plume (the bright "V" shape in bands 6 and 20). The increased NIR reflectivity can also be seen in the MSG-1 SEVIRI bands 3 (1.6  $\mu$ m) and 4 (3.9  $\mu$ m) for the entire period (1100–1400 UTC); however due to space limitations the images are not shown here.

Band 31 (Fig. 3B, top) shows the brightness temperature of the tops of these storms (BT range 200–240 K), with a distinct cold-V shape for the easternmost storm. Comparing the shape and position of the warm area inside the cold-V, this warm area matches that of the enhanced NIR reflectivity plume very well. The BTD image (Fig. 3B, middle) will be discussed separately in the next section.

Finally, the bottom panel of Fig. 3B shows a RGB composite image of bands 1, 7 and 5. While the band 1 image is shown here at its original 250 m resolution, the band 5 and 7 images were resampled to the resolution of band 1. The image shows very well the fine details of the plume; the orange (or reddish) shades are due to increased band 7 reflectivity. As can be seen here, the plume seems to have two very small sources: one on the north slope of the overshooting top,

and the other on its northwest side. Although this detail is beyond the resolution of the 1 km data, it can be resolved in the 0.5 km data (not shown here).

In Fig. 3C, the band 31 brightness temperature (198-220 K, gray scale) of the overshooting top (white) and temperature of the source of the plume (dark) can be compared with a sounding from 1200 UTC from Praha (about 150 km north of the storm). The temperature of the plume close to its source (and also further downstream) is very close to that at the top of the tropopause inversion, thus placing the plume at altitudes of 13.5 km or higher above ground level. This suggests that after the plume was generated (Wang, 2003), it may have quickly balanced its temperature with the environment by turbulent mixing. The storm height, as determined by Czech Radar Network (Novák and Kráčmar, 2002), reached at this time about 15 km; however this is likely the height of the overshooting tops, not of the anvil top itself.

Use of the other MODIS IR bands (27–36) for advanced cloud top products (Platnick et al., 2003) was beyond the scope of the present study.

## 3. Lower stratospheric moisture

Previous studies have identified that the brightness temperature is warmer in the water vapor (WV) band as compared to the IR window band above deep convective clouds (Schmetz et al., 1997; Fritz and Laszlo, 1993; Ackerman, 1996) and related this to the

![](_page_9_Figure_2.jpeg)

Fig. 4. Storms above south Bohemia (Czech Republic), Bavaria (Germany) and north Austria on 13 June 2003, 1100–1400 UTC, Meteosat-8 (MSG-1). Left column – BT (MSG band 9); right column – BTD of MSG bands 5 (WV 6.2) and 9 (IR 10.8).

presence of water vapor above the cloud tops. In the case of increasing temperature with height above the cloud, the emission from the water vapor band will include a contribution from the water vapor, which is at a warmer temperature than the cloud top, while the water vapor remains transparent to the IR window band. Therefore, the warmer the lower stratospheric water vapor will be as compared to coldest tops, the higher the BTD will be observed. A correlation between cloud top temperature and BTD can be explained by two possible ways: 1) that

Table 1 Spectral bands of the MODIS instrument

Band number	Spectral range (µm)	Characteristic	Nadir resolution (m)
Band 01	0.62-0.67	Solar band, visible	250
Band 05	1.23-1.25	Solar band, near IR	500
Band 06	1.628-1.652	Solar band, near IR	500
Band 07	2.105-2.155	Solar band, near IR	500
Band 20	3.66-3.84	Mixed solar and	1000
		thermal band	
Band 27	6.635-6.895	Water vapor	1000
		absorption band	
Band 31	10.78-11.28	Thermal IR window band	1000

Though MODIS consists of 36 different spectral bands in total, listed above are only those discussed within this paper. For further details on MODIS instrument (and all other bands) refer to King et al. (1992).

every cold overshooting top generates some amount of moisture which quickly balances its temperature with its warmer environment, or 2) that the BTD is caused by preexisting moisture, horizontally uniform, in a layer above the cloud tops.

While the older observations of the positive BTD (i.e. WV band being warmer as compared to IR window band) were based on geostationary satellite data with somewhat lower resolution, the MODIS instrument provides an opportunity to test this method at 1 km resolution. Examination of the BTD products and their comparison with IR window band 31 in Figs. 1A,B and

#### Table 2

Spectral	bands	of	the	SEVIRI	instrument
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Band number and band name	Spectral range (µm)	Characteristic	Nadir resolution (km)
Band 01 (VIS 0.6)	0.56-0.71	Solar band, visible	3
Band 02 (VIS 0.8)	0.74 - 0.88	Solar band, near IR	3
Band 03 (IR 1.6)	1.50 - 1.78	Solar band, near IR	3
Band 04 (IR 3.9)	3.48-4.36	Mixed solar and thermal band	3
Band 05 (WV 6.2)	5.35-7.15	Water vapor absorption band	3
Band 06 (WV 7.3)	6.85-7.85	Water vapor absorption band	3
Band 07 (IR 8.7)	8.30-9.10	Thermal IR window band	3
Band 08 (IR 9.7)	9.38-9.94	O3 absorption band	3
Band 09 (IR 10.8)	9.80-11.80	Thermal IR window band	3
Band 10 (IR 12.0)	11.00-13.00	Thermal IR window band	3
Band 11 (IR 13.4)	12.40-14.40	CO2 absorption band	3
Band 12 (HRV)	0.5-0.9	High resolution visible and NIR	1

For further details on SEVIRI instruments and MSG satellite refer to Schmetz et al. (2002).

Table 3

|--|

Band number	Spectral range (µm)	Characteristic	Nadir resolution (km)
Band 01	0.55-0.75	Solar band, visible	1
Band 02	3.80-4.00	Mixed solar and thermal band	4
Band 03	6.50 - 7.00	Water vapor absorption band	8
Band 04	10.20-11.20	Thermal IR window band	4
Band 05	11.50-12.50	Thermal IR window band	4

For further details on GOES I-M satellites and their instruments refer to Menzel and Purdom (1994).

3B shows a close correlation between the BTD maxima and IR BT minima, thus confirming the observations of Schmetz et al. (1997) and Fritz and Laszlo (1993). The BTD, as determined from MODIS 1 km data, ranges from about +2 K above the stratiform parts of anvil tops, up to about +4 to +7 K above the coldest storm tops.

While the 04 June 2002 MODIS data show a close correlation between BT minima and BTD positive maxima, the 13 June 2003 data show a more complicated situation (Fig. 3B). While most of the storms in the area show close correlation between BT and BTD, for the south Bohemian storm the BTD maximum is shifted to the southeast part of the storm top, with nothing in BTD resembling the cold-V. This suggests that the local warm moisture maximum above the anvil top is shifted aside from the coldest overshooting tops.

Additional insight into the patterns of BTD and BT minima may be obtained from the evolution in the GOES-8 imagery from 04 June 2002 (Fig. 2B). Examination of these images shows several interesting things. First, the northernmost storm (labeled B) maintains for most of the time a rather low BTD, although the BT itself is significantly cold and covering a large area. Other storms such as the one labeled "A" in the last image have greater values of BTD despite the BT being warmer. The situation significantly changes at the end of the period (1732 UTC), when the BTD above the storm "B" substantially increases. Another interesting evolution can be observed above the storm "A". Examination of the time series of imagery from 1702 to 1732 UTC suggests that the enhanced BTD can occur also downwind of overshooting tops, rather than always above the coldest tops as observed in other cases. One particular example is the first appearance of the overshooting top at 1645 UTC (arrow). At this time, a BTD maximum was collocated with the overshooting top as seen in the visible and cold cloud top in the 11 µm image. As the storm develops an enhanced V shape by 1715 UTC, the BTD maximum is still roughly coincident with the area of coldest cloud top. However, by 1732 UTC the BTD maximum has spread downwind of the coldest tops and covers most of the downwind anvil of the storm. The patterns of cloud top temperature and BTD evolve further by 1815 UTC as cloud tops expand and merge with adjacent storms.

However, one must be aware that for GOES-8 the resolution of WV and IR bands was different (8 km for WV band, 4 km for IR band), which is a source of BTD artifacts in regions of the storms where the pixels are located above steep BT gradients. While the (4 km) IR window band pixel may already cover only the cold top, larger (8 km) WV pixel still may be partially covering lower warmer layers, resulting in high BTD positive differences. This effect may occur either at anvil edges, or around (above) steep overshooting tops. Therefore, not every high BTD value indeed represents warmer moisture above. Careful examination of the BTD images shows several such artifacts.

This problem is fortunately solved beginning with GOES-12, as well as for MSG satellites, where the IR window and WV bands have correspondingly sized pixels. Sequence of images for the 13 July 2003 from MSG satellite (Fig. 4) confirms that in such cases the artifacts are almost absent, and also that the BTD and IR BT fields show a displacement in some of the images, confirming fluctuations of lower stratospheric moisture above storm tops. Further refinement of inferences based on a subjective evaluation of the correlation between BT and BTD could be achieved by statistically computed correlations between BT and BTD; however this was beyond the scope of this study.

One question related to the satellite observations is whether the water vapor generated by the overshooting storm tops can be easily resolved by the BTD method. In Wang (2003)'s simulation of the storm top plume formation, the temperature of a 'fresh' plume is colder than its environmental stratospheric air because it originates from the shell of the very cold overshooting dome. The plume temperature could become the same as the environmental air if the plume is 'old' enough that enough mixing with the warmer environmental air has occurred. In the latter case, the BTD method would be effective. This could be the case of changes of BTD in Fig. 2B 1732 UTC image. However, there is a need to investigate this matter in more detail because the plume temperature structure depends on several factors such as how "old" the plume is, how much water vapor it contains, and the surrounding environmental temperature. Any satellite-based BTD detection technique must take these factors into consideration. Of course, this applies not only to plumes, but to any lower stratospheric moisture generated by convective storms in general. We are planning to look into this matter further in future research.

Presently, it is not clear if the warm plumes observed in WV and IR bands (as for 13 June 2003, Figs. 3 and 4) are linked to moisture plumes or not; BTD images do not add any new information here. Should the warm plumes as seen in WV and IR bands, be moisture plumes only (without any ice particles present within them), these would be resolved in the WV band only (provided that the moisture plume is warmer than the underlying anvil top), but not in the IR window band. Since both of these bands show the same extent of the warm plume, and the BTD image shows no significant difference between the two bands, the warm plume must result from solid ice particles being present in the plume.

Another issue to be noted here is that the abovementioned BTD differences assume very similar emissivity in IR window and WV bands. Should the emissivity in IR window bands be lower for some type of ice particles as compared to WV bands, the BTD would also give positive results. However, we are not aware of any work (similar to that of Melani et al., 2003, addressing BTD at 10.8 and 12 µm) indicating such a possibility. Similarly, differences in transmissivity (WV band more transparent than IR window band) would also lead to positive values of the BTD. This effect seems to be present for some of the storms (at semitransparent portions of their anvils) from 13 June 2003, when comparing the BTD and highresolution visible images from the MSG satellite (not shown here).

## 4. Plumes on the global scale

Study of the occurrence of VIS/NIR plumes above storms in parts of the World other than Europe and the central and eastern U.S.A. is based on the data set, described in the Data section. Out of the 125 satellite data sets of storms around the globe, only 10 of them were found showing distinct plumes. These were found to occur at central Africa, Argentina, the Pacific and Indian Oceans, and the Red Sea. No attempt to search for BTD plumes (i.e. warm moisture plumes without ice particles present within them) was performed yet.

The sampling limitation of the Terra and Aqua satellites results in the low probability of observing thunderstorms in their growth and mature stages. Terra, with its  $\sim 10:00$  a.m. local crossing time in northern midlatitudes typically samples dissipating or weakening

nocturnal storms. Aqua, with its  $\sim 13:00$  p.m. crossing time, usually misses the typical late afternoon peak in thunderstorm development over land. This severely limits the total number of daytime thunderstorm observations from MODIS. A satellite with MODIS instrument at a late afternoon orbit ( $\sim 17:00$  p.m. local crossing time) would be highly desirable for research of convective storms over land during their most intense stage of development.

# 5. Summary and conclusions

The study has shown that a high resolution, multichannel instrument like MODIS can reveal details of storm tops, which are only poorly resolved by present geostationary satellites. On the other hand, despite their lower resolution, images from geostationary satellites are beneficial in the investigation of some features, such as the BTD maxima. Without geostationary satellite sequences it would have been difficult to infer the displacement of these features. However the origin of moisture plumes and their evolution in the stratosphere requires further research.

Present work has documented the similarity of anvil top features in the NIR (1.6–3.9  $\mu$ m) bands, although certain differences were present when examined in fine details. Future studies will focus more on evolution of these features based on MSG satellites.

Another result of this brief survey may be a new insight on cloud top features, namely a link between plumes above anvils and the warm wakes within cold-U/ V signatures. The MODIS instrument has enabled multispectral imaging of these features with higher resolution than previously possible. One such example is the case of 13 June 2003 which suggests an additional mechanism of the "cold-U/V" shape production in addition to those mechanisms discussed by Fujita (1982), Negri (1982), McCann (1983), Adler and Mack (1986), Heymsfield et al. (1991). The cold-U or -V shape may be produced by the masking of the cold anvil top at the storm's downwind side by an elevated warmer plume, which in some instances can be identified in the VIS/NIR bands. What remains to be explained is the mechanism that generates an identifiable plume in all the spectral bands (including the WV/IR "warm plumes"), and conditions when these develop. Perhaps the modeling of moisture plumes by Wang (2003) or Doswell and Weber (2002) and modeling of radiative properties of anvil tops and plumes above them (Melani et al., 2003) may provide further understanding of this mechanism. However, the relation between cold-U/V signatures and warm plumes should be validated on a significantly larger number of cases, with

the use of geostationary satellite observations and comparison with numerical model simulations.

In the past, various features such as cold-U/V and warm wakes, VIS/NIR plumes, BTD, or the NIR reflectivity were usually treated independently. The present generation of satellites and their instruments offers a chance to study all of these features in synergy in order to achieve a new and comprehensive view of storm top physics.

Since it was impossible to show all the images discussed in this paper in highest resolution due to space limitations, they can be obtained from the corresponding author upon request.

#### List of abbreviations

- AVHRR Advanced Very High Resolution Radiometer **Brightness Temperature** BT BTD **Brightness Temperature Difference** Czech Hydrometeorological Institute CHMI Environment for Visualizing Images ENVI Earth Observing System EOS EUMETSAT European Organization for Exploitation of Meteorological Satellites GOES Geostationary Operational Environmental Satellite Goddard Space Flight Center **GSFC** High Resolution Visible HRV Interactive Data Language IDL IR Infrared McIDAS Man computer Interactive Data Access System METOP Polar satellite of EUMETSAT MODIS Moderate Resolution Imaging Spectroradiometer MSG Meteosat Second Generation National Aeronautics and Space Administration NASA Near Infrared NIR NOAA National Oceanic and Atmospheric Administration SEVIRI Spinning Enhanced Visible and Infrared Imager
  - SSEC Space Science and Engineering Center
  - WV Water Vapor

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