MSG OBSERVATIONS OF DEEP CONVECTIVE STORMS

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ABSTRACT

Past studies based on the NOAA/AVHRR, GOES, and MODIS imagery have revealed several significant cloud top features occurring at or above cloud tops of deep convective storms. These include the so-called “cold-U/V shape” coupled with embedded warm areas, regions of increased shortwave IR (1.6 – 4 μm) cloud top reflectivity, above-anvil plumes in VIS and shortwave IR bands, and moisture possibly present above storm tops in the lower stratosphere. While in the past, most of these phenomena were documented or studied independently, at different instants in time, MSG SEVIRI offers a chance to study their evolution and evaluate possible relationships between these cloud top features.

The present work focuses on tops of convective storms over Europe, as observed by the SEVIRI instrument. The first goal of this work is to investigate the hypothesis that a cold-U/V shape can result from masking of lower cold anvil top by a warmer plume, developing above storm cloud top in the lower stratosphere. The second goal is to explore the possibility of detection of water vapor present above storm tops. Although the above-anvil plumes have been well documented in the VIS and near IR spectral bands only, latest modeling results suggest that a plume of moisture develops above the anvil before the formation of ice particles. If such a moisture plume forms, it should be possible to detect it under favorable conditions (a thermal inversion above cloud top level) from the brightness temperature difference of WV and IR window bands. This is investigated using the time continuity of the SEVIRI measurements.

1. Introduction

One of results of the AVHRR based observations of deep convective clouds dating back to late 80’s and early 90’s (e.g. Setvák and Doswell, 1991; Levizzani and Setvák, 1996) was recognition of a cloud top phenomenon which was labeled as a “plume”. Though originally recognized as a region of increased 3.7 μm reflectivity, further studies have shown that it can be found in all the solar bands, from visible to short-wave infrared wavelengths (up to about 4 µm). Major properties of plumes are summarized in Levizzani and Setvák, 1996; among these the most important ones from perspective of this paper are (1) the fact that the ice particles from which these are being formed do not seem to be generated by storm updrafts, and (2) the vertical displacement of plumes above the anvil tops.

Observational studies from 13 June 2003 (Setvák and Rabin, 2003, Setvák *et al.*, 2005) have suggested an alternative interpretation of features well known as *cold-U/V shape*[1], first documented e.g. by Negri, 1982, McCann, 1983, or Adler and Mack, 1986. In the case of the south Bohemian storm of 13 June 2003, as observed in Aqua/MODIS imagery, the warm area inside the cold-U/V shape matches exactly the outline of a plume, which is well defined in all the solar bands, and moreover also distinguished from the rest of the storm top due to its higher short-wave infrared reflectivity. Comparison with radar data (cloud top height) and a temperature profile has shown that the plume must have formed well above the tropopause, within an inversion; the brightness temperature of the plume matching the environmental temperature of the inversion. Thus, in that case the warm interior of the cold-U/V shape was unambiguously a result of masking of the colder storm anvil top by this warmer plume, which formed above it.

Since the inferences above were based on individual Aqua/MODIS images, one of the tasks of the present work was to investigate the development and temporal evolution of the cold-U/V shape and plume formation for the storm of 13 June 2003 using MSG/SEVIRI data. This topic is addressed by the first part of the paper, together with preliminary observations from similar cases in 2005.

Second part of the paper addresses first results of diagnosis of brightness temperature differences (BTD) between SEVIRI WV 6.2 and IR 10.8 bands above cold storm tops. This topic was pioneered for midlatitude convection by Schmetz *et al.,* 1997, who used for their study the Meteosat first generation imagery. In their work, they documented that the BTD between WV (5.7-7.1 µm) and IR (10.5-12.5 µm) bands was positive (up to 6 to 8 K) above cold tops of deep convective clouds not only in tropics (as documented earlier by others, e.g. Fritz and Laszlo, 1993), but also in midlatitudes. This was attributed to presence of warmer water vapor layer in the lower stratosphere. Similar results were later obtained independently by Rabin and Setvák for GOES, MODIS and MSG observations, though for a limited number of studied cases only (Setvák *et al.*, 2005).

A goal of the present work was therefore to study the BTD of MSG/SEVIRI WV6.2 - IR10.8 bands for a more representative number of cases. For this purpose, 13 days from 2005 with significant convection over various parts of Europe were processed. An analysis of these data is presented in section 3.

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[1] The appearance of a "U" or "V" shape depends mainly on the satellite perspective; when observed in polar satellite imagery close to nadir, these features tend to resemble the U-shape, while from geostationary perspective the appearance of the same feature is closer to a V-shape. Moreover, the shape also depends on the location: the outer edge of a cold area (which tends to be more a U-shape), or the warmer enclosed area, which more often resembles a V-shape. For these reasons the authors refer this feature as a ***cold-U/V shape***.

2. Plumes and cold-U/V shape formation

Figures 1 shows the same storm of the 13 June 2003 as analyzed in Setvák and Rabin, 2003 (its *Figure 2*) or in Setvák *et al.*, 2005 (its *Figure 3*). These papers document and discuss the appearance of the south Bohemian storm (arrowed in *Fig. 1a*) from perspective of the MODIS/Aqua at its 0.25 km, 0.5 km and 1 km resolutions. The MSG/SEVIRI images presented here, though of somewhat lower resolution (about 4 x 6 km for Central Europe for the 11 standard bands, and about 1.3 x 2.0 km for the High Resolution Visible, HRV), enable study of the evolution of storm top features at 15 minute intervals. Only the most significant period of the storm's evolution is shown here (between 11:55 and 12:25 UTC). Note that the first of these times corresponds to the scanning time of the MODIS/Aqua from the two other papers.

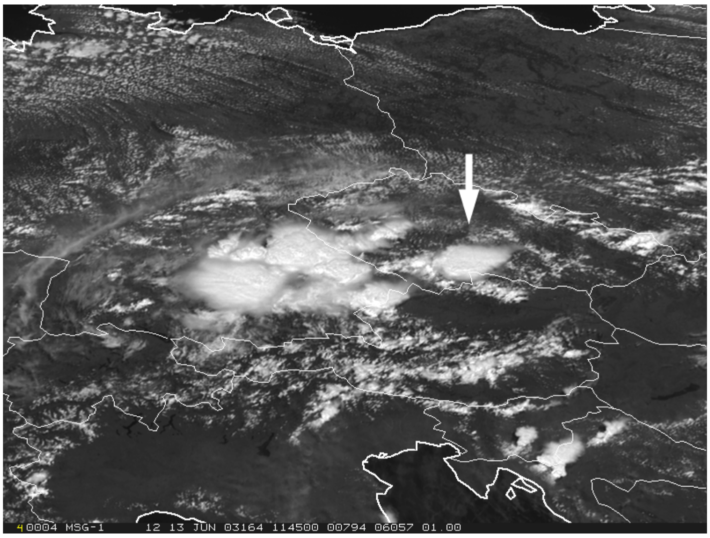

Figure 1a*. Geographical location of the storm of 13 June 2003 in south Bohemia, Czech Republic, shown in detail on Figure 1b. This image shows the storm position at 11:55 UTC.*

Data from EUMETSAT U-MARF archive, processed by Jochen Kerkmann.

Figure 1b illustrates that the cloud top features seen in MODIS imagery (in Setvák and Rabin, 2003) can be easily seen also in the MSG/SEVIRI imagery, though not as clearly due to its lower resolution. Images of the HRV (top row) show the plume originating in the southwest part of the storm, "streaming" to the east–northeast. Images in the IR 10.8 band show the cold-U/V feature being more narrow and best defined at 11:55, and widening and loosing its contrast at the later times. The third and fourth rows show the cloud top reflectivity in near (NIR) and shortwave IR bands, at 1.6 and 3.9 µm. The most obvious difference between NIR 1.6 and IR 3.9 bands is at 11:55 when the plume is barely visible in 1.6 µm, while it is well defined in the 3.9 µm band. This difference between the two bands decreases at the next two times, where the 12:10 image shows almost the same patterns in both of these bands. At 12:25, however, the 3.9 µm image shows a wider and better defined "split" plume as compared to the 1.6 µm image. These differences might be related to changes in optical thickness of the plume and to different response functions in the two bands (Rosenfeld *et al.*, 2002).

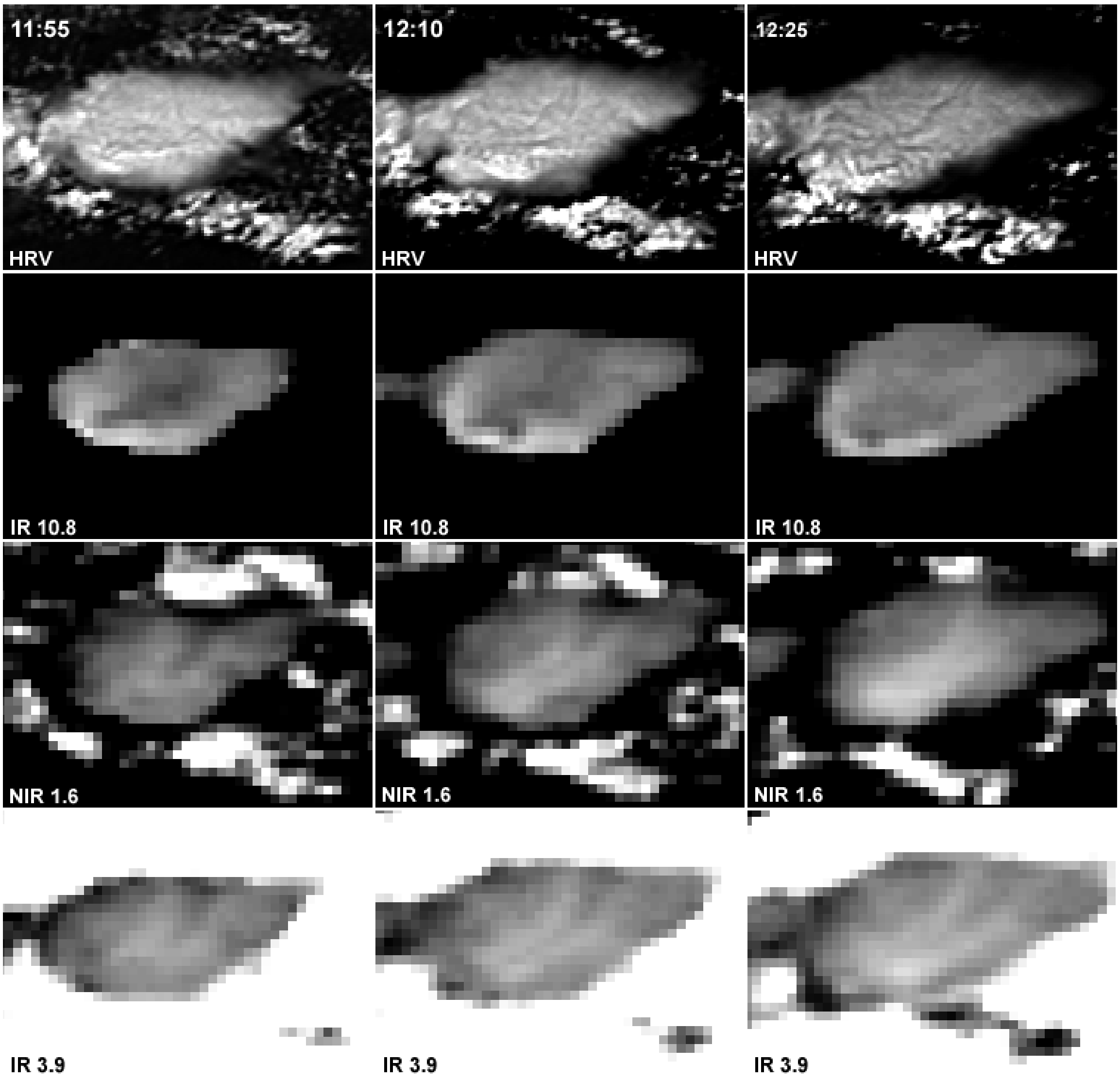

***Figure 1b**. Details of the arrowed storm from Fig.1a as observed by MSG-1 (Meteosat-8). Columns (left to right): 11:55, 12:10 and 12:25 UTC; rows (top to bottom): bands HRV, IR 10.8 (200-220 K), NIR 1.6 and IR 3.9 (shown here as reflectivity image), all scaled to the same resolution as HRV image.*

Data from EUMETSAT's U-MARF archive, images processed by MSG_RGB tool from Daniel Rosenfeld and Photoshop CS, processing Martin Setvák.

However, the most important observation from the scope of this paper is the relation between the shape of the plume as seen in HRV, NIR 1.6 and IR 3.9 bands, and the outline of the warm area found inside the cold-U/V. The best correspondence between these was at 11:55, which was also the time of the Aqua overpass. With the subsequent evolution of the storm, the warm area inside the cold-U/V appears to be wider as compared to the plume in the other bands. The southeast edge of the plume matches well the boundary between the warm and cold cloud top, but the northwest part of the warm area is wider than the plume extent there. However, it is impossible to exclude the possibility of a very thin plume edge, which would impact the IR 10.8 band while remaining invisible in the HRV and shortwave IR bands (Melani *et al.*, 2003). A similar possibility also applies to the appearance of the storm before the times shown here. The cold-U/V first appears at 11:25, but the plume can be observed first at 11:55. Also, the subsequent development of the storm no longer shows such a correspondence of the plume between the solar and IR10.8 bands. The plume appears warmer most of the time, but not as significantly as at the times shown in *Figure 1b*. The last image when the plume was well detectable in all the bands (solar and IR10.8) was 13:55. The plume disappears at 14:10. The cold-U/V shape was also present for this entire period, though not as well pronounced as in the images from 11:55 to 12:25 in *Fig 1b*. The storm was a single-cell right-mover (in radar imagery) from its early stage at about 11:30 until about 14:30, when the cell weakens and disappears. Occurrence of such well developed severe storm (6 cm hail) so early in the day is unique for this region.

No unambiguous conclusions either in support or against the masking mechanism can be made from this single case. Although, the observations seem to support the hypothesis at certain times, they are uncertain for other periods of the cloud's evolution.

From the examination of the 13 significant convective days in 2005, no such similar well-defined plume was found (in solar bands, including HRV). In a few cases, a faint plume could been observed. Also, the plume matched the shape of the warm interior of related cold-U/V well only in some of these cases. Therefore, there is a need of more cases with well-defined plumes in solar bands to determine the frequency of plume position and shape with respect to the warm interior. Since the plume can appear warm only when developing at warmer inversion level, it is clear that these studies must be carried out together with examination of close-by soundings.

3. BTD (WV6.2-IR10.8) above storm tops

The BTD of MSG/SEVIRI WV6.2 - IR10.8 bands and its correlation with the brightness temperature (BT) of IR10.8 band itself, were evaluated on 13 days from 2005 with significant convection over various parts of Europe (mainly its central and western parts). The most recent available data at the time of analysis is from August 2005, so no early autumn storms from Mediterranean region were included into this study.

Data were obtained from the archive of CHMI (received by EUMETCast system); processing was done by VCS *2met!* interactive processing utility, visualization and analysis was done by ENVI 4 software, using XPIF format plug-in.

In majority of the examined cases, the BTD field is very closely related in a spatial sense to the BT IR10.8 field, with highest BTD values found above the coldest BT spots or areas. This is in agreement with the earlier observations (Schmetz *et al.*, 1997, Setvák *et al.*, 2005). It should be noted here that such close correlation between BTD and BT could be due to a presence of a widespread moisture above the storms in a layer which is warmer than the anvil top temperature, rather than locally maximum moisture above the coldest spots.

Of particular interest to this study are cases where larger positive values of BTD may not be collocated with coldest BT (hereafter referred to as “BTD anomalies”). Such BTD anomalies were first observed in GOES and MODIS imagery (Setvák *et al.*, 2005). In contrary to the closely correlated BTD and BT, these BTD anomalies could be attributed to: 1) locally increased amounts of lower stratospheric moisture, perhaps generated from below by storm updrafts (Wang, 2003), or 2) locally increased temperature of the moisture. The following explores the evolution of BTD anomalies in time, and their relation to storm’s structure.

Among the 13 examined datasets, only a few cases were found showing some degree of these “BTD anomalies”; the most significant of these are storms of the 28 June 2005 in northern France (*Figure* 2, below).

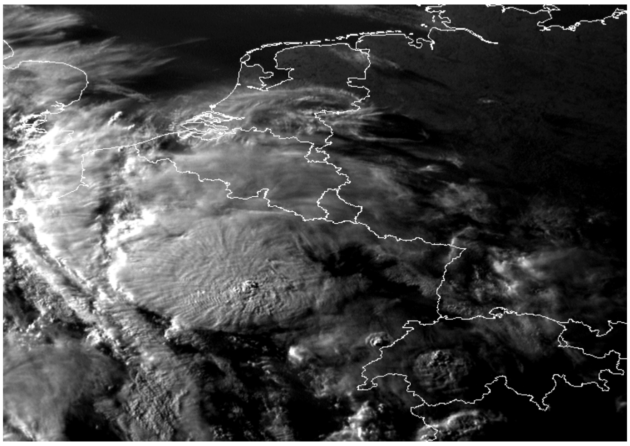

Figure 2a *(left): Storm of 28 June 2005, north France; geographical location of the storm at 18:45 UTC; MSG-1 HRV band. Zoomed images below (in Fig.2b) show details of the storm in center of this image.*

All data and images of the Figure 2: CHMI MSG archive, processed by M.Setvák.

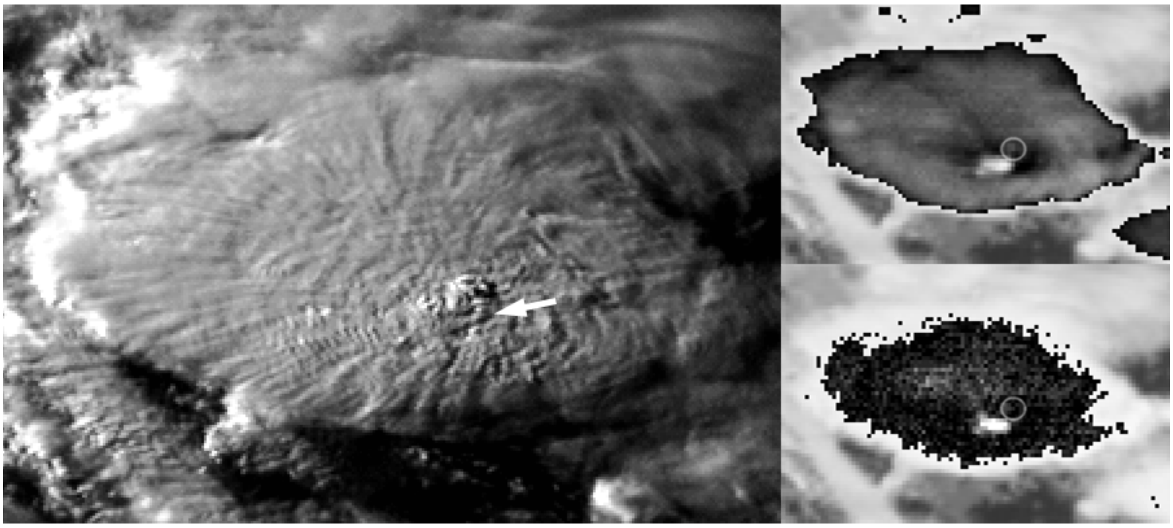

Figure 2b. *HRV image (left), IR10.8 with enhanced BT 205-220K (top right), and BTD of bands WV6.2 and IR10.8, range 0 – 6K (positive values only), superimposed over IR10.8 image (bottom right). Arrow in HRV image indicates a possible plume, circle in the images at right indicates position of the overshooting tops as seen in HRV (northwest of the arrow). For further details see the text.*

The storms developed at about 14:00 UTC. From their early stage, these storms exhibited the most typical characteristics: positive values of BTD above most of the anvil top, and their maxima closely matching the BT minima. However, between 16:15 – 17:15 it was possible to detect the first smaller scale unambiguous BTD anomaly. At 18:45 (*Fig. 2b*) the storm exhibited the highest positive BTD value computed from the 2005 MSG dataset, 5.7 K. This BTD feature appeared above a local cold spot of 206 K, with its core shifted by 2 pixels (about 8 km) west of the coldest spot. Both are displaced southwest of the overshooting tops, inside a feature resembling a plume in the HRV (arrow in *Fig. 2b*). It should be noted that at the time when the lowest BT was observed for this storm (17:45, 202 K), the BTD was only 3.4 K.

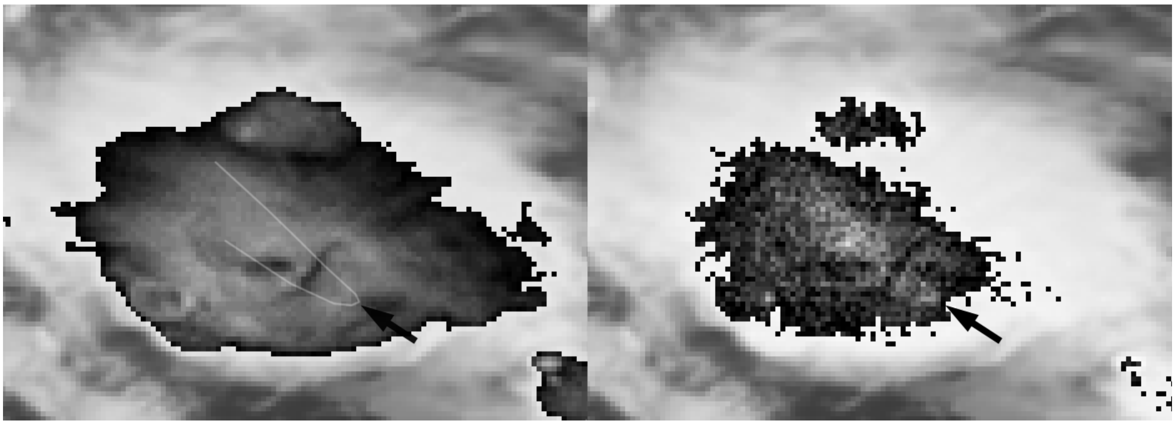

Figure 2c. *The same storm at 20:30 UTC; IR10.8 with enhanced BT 205-220 (left image), and BTD 0 – 6K (right image). Arrow in the BTD image (right) indicates a feature resembling a plume, outline of which is superimposed over the IR10.8 BT image. In this case the BTD anomaly is obvious. For further discussion see the text.*

The most interesting development occurred between 19:00 and 21:15, when it was possible to detect for this entire period a BTD feature resembling a larger plume, spreading over most of the anvil top. *Figure 2c* shows this BTD plume at 20:30, the arrow on the BTD image indicates the apparent source of the plume. The outline of this feature is superimposed over the BT image (left). Inside this feature the average BTD is higher as compared to its surroundings by about 1 to 1.5 K.

If this BTD feature is indeed a manifestation of warmer stratospheric moisture, it is consistent with modeling results of moisture plumes, (Wang, 2003). The model developed a moisture plume several hours after the onset of deep convection, which is similar to that observed here with the 28 June 2005 storm.

However, the BTD features can also be explained by emissivity and transparency effects, in combination with vertical temperature gradients at the upper levels of the storms (Daniel Rosenfeld, personal communication 2005). Which of the two effects is indeed responsible for the positive BTD values over most of the storm tops and for the observed BTD anomalies remains to be validated by means of radiative transfer modeling, which is beyond the scope of this paper.

4. Summary and conclusions

The possible link between cold-U/V shape formation and plume masking mechanism is supported by some of the observations presented here. However, not every case examined was conclusive regarding identification of the plume's boundaries and location relative to the warm BT region. Examination of a larger number of cases will be required to substantiate the frequency and significance of masking of cold anvil tops by warmer plumes.

The BTD (WV6.2-IR10.8) anomalies have been unambiguously illustrated in MSG/SEVIRI data. In at least in one case, the anomaly had the appearance of an above anvil moisture plume. In several other cases (not shown), the increased values of BTD usually appeared at a later stage of storm's life cycle. In those cases, the outline of these BTD anomalies was irregular such that they did not resemble a plume.

The observations and previous model results suggest that these BTD features could be a manifestation of moisture in the warmer, lower stratosphere, emanating from storm tops. However, this remains to be validated by RTM simulations.

Acknowledgements

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Bibliographic References

ADLER, R.F., R.A. Mack, (1986): Thunderstorm cloud top dynamics as inferred from satellite observations and cloud top parcel model. J. Atmos. Sci., **43**, pp 1945-1960.

FRITZ, S., I. Laszlo, (1993): Detection of water vapor in the stratosphere over very high clouds in the tropics. J. Geophys. Res., **98** (D12), pp 22959-22967.

LEVIZZANI, V., M. Setvák, (1996): Multispectral, high-resolution satellite observations of plumes on top of convective storms. J. Atmos. Sci., **53**, pp 361-369.

McCANN, D.W., (1983): The enhanced-V, a satellite observable severe storm signature. Mon. Wea. Rev.,**111**, pp 887-894.

MELANI, S., E. Cattani, F. Torricella, V. Levizzani, (2003): Characterization of plumes on top of a deep convective storm using AVHRR imagery and radiative transfer model simulations. Atmos. Research, **67-68**, pp 485-499.

NEGRI, A.J., (1982): Cloud-top structure of tornadic storms on 10 April 1979 from rapid scan and stereo satellite observations. Bull. Amer. Meteor. Soc., **63**, pp 1151-1159.

ROSENFELD, D., E. Cattani, S. Melani, V. Levizzani, (2002): Considerations in daylight operation of 1.6 µm vs 3.7 µm channel on NOAA and Metop satellites. Proc. The 2002 EUMETSAT Meteorological Satellite Conf., Dublin, Ireland, EUM P 36, pp 64.

SCHMETZ, J., S.A. Tjemkes, M. Gube, L. van de Berg, (1997): Monitoring deep convection and convective overshooting with METEOSAT. Adv. Space Res., **19**, No. 3, pp 433-441.

SETVÁK, M. and C.A. Doswell, (1991): The AVHRR channel 3 cloud top reflectivity of convective storms. Mon. Wea. Rev., **119**, pp 841-847.

SETVÁK, M., R.M. Rabin, C.A. Doswell and V. Levizzani, (2003): Satellite observations of convective storm top features in the 1.6 and 3.7/3.9 µm spectral bands. Atmos. Research, **67-68**, pp 607-627.

SETVÁK, M., R.M. Rabin, P.K.Wang, (2005): Contribution of MODIS instrument to the observations of deep convective storms and stratospheric moisture detection in GOES and MSG imagery. Atmos. Research *(submitted in March 2005; accepted for press in*

September 2005).

WANG, P.K., (2003): Moisture plumes above thunderstorm anvils and their contribution to cross-tropopause transport of water vapor in midlatitudes. J.Geophys.Res., **108** (D6), pp AAC 5.1 – 5.15.