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Satellite-observed cold-ring-shaped features atop deep convective clouds

Martin Setvák [a,*], Daniel T. Lindsey [b], Petr Novák [a], Pao K. Wang [c], Michaela Radová [a,d,h], Jochen Kerkmann [e], Louie Grasso [b], Shih-Hao Su [c], Robert M. Rabin [f,g], Jindřich Šťástka [a,h], Zdeněk Charvát [a]

[a] Czech Hydrometeorological Institute, Na Šabatce 17, CZ-14306 Praha 4, Czech Republic
[b] NOAA/NESDIS/RAMMB, CIRA/CSU, 1375 Campus Delivery, Ft. Collins, CO 80523, USA
[c] University of Wisconsin-Madison, 1225W. Dayton Street, Madison, WI 53706, USA
[d] Institute of Atmospheric Physics, AS CR, Boční II 1401, CZ-14131 Praha 4, Czech Republic
[e] EUMETSAT, Am Kavalleriesand 31, D-64295 Darmstadt, Germany
[f] NOAA/National Severe Storms Laboratory, 120 David L. Boren Blvd, Norman, OK 73072, USA
[g] Space Science and Engineering Center, 1225W. Dayton Street, Madison, WI53706, USA
[h] Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, Praha 8, Czech Rep.

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ABSTRACT

This paper focuses on deep convective storms which exhibit a distinct long-lived cold ring at their cloud top, as observed in enhanced infrared (IR) window satellite imagery. The feature seems to be closely linked to a similar phenomenon, cold-U/V (enhanced-V) shape, or in general to storms which exhibit an enclosed warm spot or larger warm area downwind of the overshooting tops, surrounded by colder parts of the storm anvil. While storms exhibiting some form of warm spots seem to be quite common, storms exhibiting distinct cold rings or cold-U/Vs are significantly less frequent. The cold-ring feature is described here for storms which occurred above the Czech Republic and Austria on 25 June 2006. Compared to other cold-ring-shaped storms, this case was extraordinary not only by the magnitude and duration of the cold ring and its central warm spot, but also by storm cloud-top heights, reaching 16-17 km, as determined from ground-based C-band radar observations. The paper also addresses a possible link between cold-ring-shaped storms with those exhibiting a cold-U/V (enhanced-V) feature, indicating (based on model results) that the stratification and wind shear just above the tropopause are key conditions for the cold-ring to exist. The case from 25 June 2006 also shows that the cloud top height, derived from satellite radiances, has significant error when applied to this particular type of storm. Finally, we discuss the potential of the satellite-observed cold-ring feature as an indicator of storm severity.

1. Introduction

Cloud top brightness temperature (BT) retrieved from satellite data in the IR window band (10-12.5 µm) has been used to estimate cloud top height (CTH) before data for CO2 slicing become available. In principle the BT can be converted to CTH with sufficient accuracy — as long as the cloud top is sufficiently opaque, is located under the tropopause and only adiabatic processes are involved (excluding e.g. mixing with storms top's environment). However, many studies from the 1980's documented errors in the CTH derived from satellite BT measurements due to limited resolution and physical effects. An example is the case of strong convective storms with their highest tops penetrating the tropopause, overshooting the rest of the storm anvil by hundreds of meters up to several kilometers into the warmer lower stratosphere. Certain characteristics of the cloud-top BT field surpass simple interpretation, with various warm or cold cloud top

* Corresponding author. CHMI, Na Šabatce 17, CZ-14306 Praha 4, Czech Republic. Tel.: +420 244033288; fax: +420 244032442.
E-mail address: setvak@chmi.cz (M. Setvák).

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features resulting from complex storm top processes (e.g. Adler and Mack, 1986). Warm spots, cold rings and cold-U/Vs (or *enhanced-Vs*) are the most common examples of such features, and in these instances the BT field cannot be directly linked to CTH.

Storms exhibiting *cold rings* or *cold-U/V* shapes belong to a category of storms whose tops exhibit some form of cold/warm couplets. Under favorable conditions almost every major overshooting top generates a downwind counterpart, a warm spot of varying horizontal extent, BT difference from the surrounding anvil, and duration. Warm spots embedded within cold anvil tops were first reported some 30 years ago, on the basis of GOES/SMS imagery (Mills and Astling, 1977). Typically, based on Meteosat Second Generation (MSG) imagery, these are only transient features, disappearing shortly after the collapse of their "parent" overshooting top. We are not aware of any recent observational study documenting in detail the life cycle of overshooting tops and their coupled warm spots. Since knowledge of these relatively simple phenomena is essential for a proper understanding of more complex features such as cold rings and cold-U/V shapes, a study of this nature is certainly warranted.

In the early 1980's, Negri (1982), Fujita (1982), McCann (1983), Heymsfield et al. (1983a) and several others documented a special category of storms, exhibiting a feature they called an *enhanced-V*. The original name of this feature reflects the fact that it was revealed in *enhanced IR imagery*. In this paper, a more physically descriptive term will be used in reference to this feature: a *cold-U* (or *cold-V*, depending on the actual appearance of the feature, or generally *cold-U/V*) shape. Follow-up works, including Heymsfield et al. (1983b), Schlesinger (1984, 1988), Adler et al. (1985), Adler and Mack (1986), Heymsfield and Blackmer (1988), and Heymsfield et al. (1991) discussed the origins of this feature and namely of the warm regions enclosed by this feature, the *close-in warm area* (CWA) and the *distant warm area* (DWA). They also documented a close link between these features and the storm severity. Schlesinger (1988) specifically examined the effect of stratospheric lapse rate on the storm top structure. An example of a storm with a cold-U shape as observed by MSG satellite is shown in Fig. 1, top. Recently, the topic has risen in importance again, in relation to gravity wave breaking studies, e.g. Wang (2007a, b), *pyro-Cb* storms, e.g. Luderer et al. (2007), or possible nowcasting applicability, e.g. Brunner et al. (2007). As will be shown in Section 5, there appears to be a very close link between cold-U/V-shaped storms and storms with a cold-ring feature atop their anvils.

Cold-ring-shaped storms are similar to those with a cold-U/V shape, differing only by the closed shape of the cold feature (Fig. 1, bottom). The cold ring entirely encloses the *central warm spot* (CWS). Despite the high probability that the origin of the CWS is similar to the origin of CWA inside a cold-U/V-shaped storm (and therefore both warm features might be named the same), for practical reasons we prefer to distinguish the two features with different names. In general, the CWA and CWS can be commonly referred to as *embedded warm area* (EWA). It should be stressed here that the cold ring represents the "anvil background", attaining its ring-like shape due to the presence of a CWS. Therefore, to explain the presence of a cold ring, the key seems to be in proper understanding of the CWS feature.

Several cases of cold-ring-shaped storms have been previously observed (either unpublished, or documented briefly, e.g. Dotzek et al, 2005). It was the launch of the MSG satellite with its *Spinning Enhanced Visible and InfraRed Imager* (SEVIRI, Schmetz et al., 2002), which began a period of more frequent observations over Europe (Setvák et al., 2008). This paper addresses central-European storms; however, similar cold-ring shaped storms have also been observed elsewhere.

2. Data sources and processing

The MSG SEVIRI data used in this paper were received, archived, processed and visualized by Czech Hydrometeorological Institute's (CHMI) VCS Space *2met!* system (http://www.vcs.de/spacecom.html). Other MSG data referred to but not shown in the paper were received and processed either by CHMI or EUMETSAT satellite processing and visualization systems. The brightness temperature color enhancement used in this paper complies with that recommended by the EUMETSAT's Convection Working Group (http://convection.satreponline.org/).

Radar images in this paper are based on volume data from operational measurement of the Czech weather radar network (CZRAD). The CZRAD consists of two C-band weather radars (Novák, 2007), which cover the entire area of the Czech Republic and its vicinity. All of the radar images were processed and visualized by in-house-developed software (Novák, 2007). Additional details of the radar data processing can be found in Section 4.2 and the Appendix A.

3. General characteristics of cold-ring-shaped storms

In general, storms exhibiting some form of embedded warm area or short-lived smaller-scale warm spots, forming downwind of the individual overshooting tops, are quite common in MSG imagery over Europe. It seems that their occurrence is supported by some specific airmass types and wind shear; on some days they tend to form at cloud top of almost every storm over larger regions, while on other days all the storms have a "regular" appearance, without any trace of a warm spot. This aspect is presently being studied by co-authors of this paper in more detail, both observationally and theoretically, using numerical models. Most of the overshooting top-warm spot couplets have lifetimes of typically up to 2 or 3 MSG 15-minute scan cycles; however, some of them can be found in a single 5-minute rapid scan only. There are several cases of long-lived (of the order between 1 to 2 h) and large-sized cold-ring-shaped storms documented over the last few years. The majority of these produced some form of severe weather (*Image Gallery* at http://www.eumetsat.int/).

Until now, there has been no quantitative definition of a cold-ring-shaped storm, based on the BT difference between the cold ring minimum and CWS maximum, BT uniformity within the cold-ring feature, and its duration. Therefore, for the purposes of this paper, we define the cold-ring-shaped storm based on its duration only, not addressing the other characteristics. To exclude the short-lived transient events, we define a "cold-ring-shaped storm" as only those cases where the cold ring and the embedded warm area can be unambiguously traced for a period exceeding the typical lifetime of a common, non-supercellular storm cell, i.e., at